New generation of network access controller : an SDN approach

Benjamin Villain

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Benjamin Villain

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Dr. Lila Boukhatem	Rapporteur, Université Paris-Sud, Orsay, France
Dr. Nicolas Normand	Rapporteur, Université de Nantes, Nantes, France
Pr. Jean-Louis Rougier	Examinateur, Télécom ParisTech, Paris, France
Dr. Marcelo Dias de Amorim	Examinateur, UPMC (Paris 6), Paris, France
Dr. Julien Ridoux	Examinateur, Synclab, Australie
Pr. Khaldoun Al Agha	Examinateur, Green Communications, Paris, France
Pr. Guy Pujolle	Directeur de thèse, UPMC (Paris 6), Paris, France
Dr. Patrick Borras	Co-directeur de thèse, Ucopia, Montrouge, France

Cette thèse est dédiée à mon grand père.

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Abstract

This dissertation presents the importance of cross-layer network information for network applications in the context of network access control.

After describing the ins and outs of network access control and its crucial needs of cross-layer data, the dissertation exposes a novel architecture in which a network access controller is mutualized in the Cloud. This architecture allows to address a key market segment for clients unwilling to buy expensive hardware to control their network. Multiple challenges come into play when hosting the controller remotely. Indeed cross-layer information are no longer available which prevents the controller from correctly controlling users activity.

A first implementation to share cross-layer information is presented in chapter 2. It leverages specialized session border controllers to send these data in the application protocol, here HTTP. Then chapter 3 presents an innovative solution for the cross-layering problem which allows to intrumentalize network flows with SDN protocols. The solution focuses on a web portal redirection but is extendable to any kind of protocols. The implementation permits to intercept and modify flows in order to input cross-layer data within another network protocol. This solution was implemented in the OpenDaylight OpenFlow controller and shows great results.

The mutualized approach coupled with the SDN cross-layer framework allow to build flexible networks with almost no configuration of on-site equipments. The central network controller reduces the overal cost of the solution by being mutualized among multiple clients. Moreover, having the ability to intrumentalize network traffic in software allows to implement any kind of custom behavior on the runtime.

Contents

Introduction

Network applications are built on top of protocols to transmit information between multiple entities. IP address, MAC address, port numbers are examples of valuable information transiting on the network which allow pieces of software to take decisions: "where to forward a packet ?", "which application to send data to ?". But information retrieved from a single layer might not be suffisiant for applications, especially when they implement custom behavior. Routing decisions based on signal strength in wireless mesh networks [22] [21] [18] [10], handover [39] [29], link failure detection [61] or QoS in mesh networks [74] are examples of applications which require cross-layer information in order to correctly take decisions. While these subjects have a number of related contributions, little concrete implementations exist. Indeed they require the modification of critical pieces of an Operating System's core, the Network Stack. Despite being critical, the Network Stack is also a complex piece of code because it implements complicated protocols. Additionally, custom implementations introduce compatibility issues between various systems making concrete deployements even harder.

This thesis tries to bring a new angle to the cross-layering problem using Software Defined Networking protocols. Leveraging the capacity of such protocols to externalize network topology information, a generic cross-layering framework can be implemented. For industrial reasons, this presentation focuses on Network Access Control applications which map a user identity with a network device. Such applications extensively use cross-layer information, from the physical layer to the application layer to identify a device, filter its traffic or even build custom routing tables. The present work aims at providing a system which share cross-layer information with remote actors in order to provide Cloud-based Network Access Controllers.

Over the past ten years, the quality of service provided by Internet

access vendor has been greatly enhanced. The deployment of high-speed ADSL [25] links and optical fibers played a key role at bringing high speed bandwidth Internet access [38] to everyone. In the mean time, the physical access network moved from wired to wireless links [55] [58] and devices are now mobile. Laptops, smartphones or tablets are examples of the trend in the hardware market. Users now have the capacity to associate with foreign Wi-Fi networks easily. Moreover, thanks to the links capacity increase, an Internet access can be shared with multiple users with no noticeable effect.

Helped by the growth of the Wi-Fi industry, the number of public opened networks, known as *hotspots*, has reached a point where it is possible in many city inside Europe or the United-States to gain Internet access free of charge. Restaurants, hotels, public venues or even public transport are offering Wi-Fi connectivity to their guests, sometimes in exchange for personal information. Internet providers leverage the homenet boxes setup in every home to provide their own hotspot available for their clients only.

On the other hand, opening a network to guest users brings all kinds of problems related to security and traceability. Security is an obvious issue when welcoming guests as they might have access to sensitive resources inside the private networks, eavesdrop on communications or even take over some machines. As a result, the guest network has to be isolated from the rest of the private network in order to protect critical resources. Regarding traceability, governments have rapidly understood the threat of hotspots because of the anonymity they provide to end-users. When two users from the same *Local Area Network* access a server on the Internet, it is unable to differentiate them from a network point of view. Because private networks implement a *Network Address Translation* to access the Internet, every packets emitted from the LAN share the same source. This public address is thus shared amongst all users of the same hotspot. In order to prevent ill-advised users from using public networks to evade the law, many countries made the Internet access owner liable for its usage. As a result, people and companies willing to share their Internet access need to control their visitors: who are they ? what resources did they access during their journey ?

A dedicated appliance is required to implement these tasks. Various hardware solutions exist in the market, either as Wi-Fi access points or smart gateways, but they are expensive and usually hard to setup. This explains partially why today only companies can afford them and provide

Internet hotspots.

This thesis aimed at developing a new way of thinking guest access architectures in private networks. It intends to reduce the global cost of the network access controller by mutualizing them among a multitude of clients. This network access controller, hosted in the Cloud, interacts with smart Wi-Fi access-points present on each site. Two types of smart Acccess-Points are considered in this thesis. The first category is Wi-Fi access-points already available on the market. They implement dedicated features to control user access, gather cross-layer information and interact with remote captive portals. The second category consists in implementing a border session controller using SDN protocols. The idea is to abstract the hardware in order to implement a generic interface between on-site equipments and the remote controller to exchange cross-layer data.

SDN protocols, such as OpenFlow, allow a network equipment to delegate part of its forwarding decisions to an external controller. This gives the opportunity to extend hardware features from controlled software. SDN enabled equipments are rapidly growing especially regarding OpenFlow. Hardware from core to access network including Wi-Fi access-points are now including SDN capabilities. Even non-eligible networks can benefit from SDN technologies thanks to regular computers. For example, the Linux kernel is able to run software routers and switches via the Open-VSwitch project [16] which implements some SDN features.

Given the SDN market growth, in few years the majority of network equipments will be SDN capable. Having the ability to build session border controllers from any generic hardware presents a great opportunity to control any network without the need of specific hardware.

The contributions presented in this document have been published in a couple of International conferences and a European patent has been filled after resolving the biggest technical challenge of this Ph.D.

Context

This thesis, started in 2012, is the result of the collaboration between the LIP6 and Ucopia Communications. It is an industrial thesis combining research subjects with industrial problematics. Ucopia is a Paris based company created in 2002 at the UPMC. UCOPIA develops and markets solutions enabling mobile users to achieve simple, rapid and secure Internet

access on public and private Wi-Fi networks. Whether at home, at the office, in a hotel or shopping in the street, UCOPIA delivers an outstanding experience to the mobile users.

UCOPIA also enables business organizations deploying Wi-Fi networks to best engage with their users, enhance loyalty and create new revenues opportunities. With UCOPIA, hotels, stadiums and airports, shopping malls and retail chains increase customer satisfaction and generate more revenue. As an example, the average revenue per connected fan during the last Super Bowl was $100.

UCOPIA solutions comprise a comprehensive combination of software, appliance and cloud services serving small to large customers. More than 10,000 UCOPIA solutions are deployed and maintained by UCOPIA expert partners all over the world.

The purpose of this thesis was to improve of the Ucopia solution with a scientific approach. In the mean time, a large amount of the Ph.D has been dedicated to develop roadmap features which required technical expertise in various fields including network and system programming, scripting, debugging, database management, HMI development and many more.

All the work presented in this document, either scientific or industrial, has been in the vast majority done by the author of this thesis. Although it has contributed to a wide range of other tasks, they are not in the scope of this manuscript.

Structure of the dissertation

The present dissertation is organized around three chapters. *Chapter 1* makes an in-depth coverage of network access control in private networks. It covers user authentication methods with different types of secrets, communication protocols from the user device to external user management servers and techniques to control user network activity. This chapter aims at giving enough background information to the reader in order to thoroughly understand the key points of network access control.

Chapter 2 then presents a new architecture in which the Ucopia controller is hosted outside the access network. This architecture responds to an industrial demand consisting in controlling multiple distant networks with a unique controller. After identifying the technical locks, concrete solutions implemented inside the Ucopia controller are presented. All these

developments are part of the Ucopia solution since version 5.0 released in early 2014. Projects to equip stadiums, train stations and conference centers already benefit from this architecture.

Finally *Chapter 3* presents the main contribution of this thesis: using OpenFlow equipments as session border controllers. After introducing OpenFlow, few limitations are spotted preventing to acquire mandatory information from *Chapter 2* in the Ucopia controller. To overcome this lock, a technical solution implementing a web redirection only using OpenFlow equipments is presented. A patent was filed in order to protect this invention. After dealing with some implementation details, a performance analysis is made to ensure the implementation scales. The results demonstrates that the prototype can handle at least thousands of users alone. Moreover the controller can be duplicated in order to increase the overall capacity.

Chapter 1

Access control in private networks

During the last ten years, private networks have shifted from delivering services to individuals belonging to the same organization, to providing network access for occasional guests. Prior to this shift, the user population used to be trusted: office colleagues, family, but now, strangers also use the same infrastructure. Aliens are de facto untrusted that is why they need special attention. Company finance records, source code or clients databases are examples of sensitive data stored inside private networks. Obviously, part of these data has to be available for authorized users but the guest population has to be excluded.

An analogy can be made with a theater. The building is split into different sections: the scene, the bleachers, the backstage. Depending on its identity, an individual will be authorized or not to access a section of the theater. For instance, an actor is able to go wherever he wants whereas a spectator can only go seat in the public. The notion of "identity"is really important because it tells the category in which the user belongs. Once known, and shared among all security guards, each checkpoint is able to decide whether a person is allowed to enter the area or not.

Similarly in networks, the user identity is the keystone of the security model. Indeed, given a user profile, one can derive a set of usable network services, grant access to specific areas of the network or even enhance quality of service. The identity recognition system has to provide a certain level of trust depending on the criticality of the information system. For example in real life, a military base has stronger identity checks than a movie theater. Failing to recognize an identity theft can lead to unauthorized

access to sensitive resources.

To sum up, the access network has to identify users when they connect, compartmentalize itself into different zones and ensure that users are entitled to access them and finally authorize user network traffic based on their allowed services: web, mail, file transfer... In order to verify an identity, the user has to prove it to the system. Passports and ID cards are not easily usable for computers as they have to be scanned in order to verify their authenticity. Moreover the identity of a network user is not necessarily its real name and these documents provide personal information. As a result, authentication systems use a secret held by the user, in the form of exchangeable data: either textual (passphrase) or in binary (cryptographic keys). The combination of a unique identifier and its secret allows the system to uniquely identify a user. If the secret is secured enough that nobody else can access it, identity theft is prevented. A communication channel must also exist between each user and the recognition system. This channel can be encrypted, providing confidentiality, or not which could expose the secret to other users.

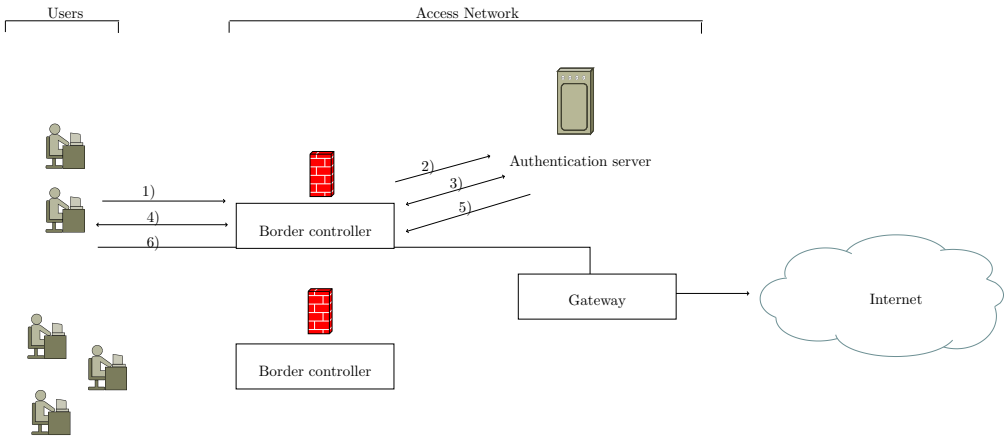
The goal of this chapter is to present the different notions which come into play when securing a network. User authentication methods are first detailed in section 1.1. Then different protocols are presented in section 1.2, they provide the communication channels permitting the transfer of authentication data. And finally section 1.3 describes different techniques to control user traffic on the runtime.

1.1 Authentication

A critical aspect of access control lays in the verification of users identity, either they are human or non-human. In real-life official documents such as passports or ID cards are commonly used to identify citizens. The security of these documents is provided by a special footprint almost impossible to reproduce. In computer science, authentication is widely used, from a simple login inside a computer to a military grade mutual authentication between two machines. It outlines different needs for different applications in terms of security, user-friendliness and setup ease.

The general idea of user authentication is to ensure that somebody is the one he says he is. Typically, each user is being assigned a unique identifier which represents its identity within the system. A username or an email

address are examples of identifiers used everyday. A secret is attached to each identifier and shared with the user so the system knows, when he provides the correct secret, it is the right person. Each user holds its own secret and the authentication server records all the secrets for every users in the database. Secrets might have multiple forms, either symmetric or asymmetric. A symmetric secret is a secret that is exactly the same for the user and the authentication server. Figure 1.1 shows a simple password-based authentication. The user sends its password along with its identity so the server can verify it has the same recorded information. Because the secret is both known by the user and the server, attackers can focus both of them in order to retrieve secrets. For asymmetric secrets, the client and the server store different kind of information: public and private keys. Basically, the keys work in pair so data encrypted by one can be decrypted by the other. The server then challenges the user to provide enough decrypted data to prove he owns the private key. Here attackers need to steal the user's private key in order to gain access to the network because the server does not store the user secret. A detailed description of asymmetric authentication is done in section 1.1.3.



1. Bob demands access
2. initiates authentication request for Bob
3. asks Bob's secret
4. exchange secret
5. authorizes Bob to access the network
6. Bob uses network services (e.g. web, mail)

Figure 1.1 – Simple password-based authentication between a user Bob and an authentication server

This section presents the basics of authentication starting with identity management. It then presents the main authentication schemes outlining their benefits and drawbacks.

1.1.1 Identity management

Many applications, not only in computer science, need to identify entities uniquely. For instance in France, each citizen has a unique social security number which is used in various situations including medical acts, tax payments and welfare. Commonly, an identity is represented by an identifier which takes the form of a name, a label or a number. It represents in a specific context an entity of the system. This identifier can be automatically generated, either randomly or based on concrete elements, or chosen. Typically in computer science, many systems use a user login to identify users. The neat aspect is that they can choose their login so they can better remember it, as long as it is not already used by another user of the system.

In a global system, identifiers might contain a namespace to identify the service provider to which the login belongs. For example, let's take the email address *john.doe@provider.com*. It identifies the user *john.doe* within the provider *provider.com*. It is separated by the @ character into two parts: the right part is the service provider in charge of the user account, whereas the left part represents the user identifier within the service provider's system. To authenticate the user John Doe, one needs to route the authentication request to *provider.com* authentication service. Authentication routing consist in performing a user authentication on a distant service provider, possibly with multiple authentication servers in between. Authentication routing is a widely used technique because it allows a user to be authenticated by its service provider from a foreign location. This type of setups is detailed in section 1.2.2.

1.1.2 Password

The password authentication is probably the most used nowadays especially for common users. It consists of a shared secret between the user and the authentication server. The server stores the user's identifier along with its password. The password can be stored in two different formats: plain text or hashed. Storing a password in plain text is not advisable because

Algorithm	Input	Value	Distance
MD5	foo	d3b07384d113edec49eaa6238ad5ff00	27
	foO	add5397a6cc7d134fea80840a8b18b21	
SHA-1	foo	f1d2d2f924e986ac86fdf7b36c94bcdf32beec15	34
	foO	029b92234decededf8f5914217043823b1eb62ed	
SHA-256	foo	b5bb9d8014a0f9b1d61e21e796d78dccdf1352f23cd32812f4850b878ae4944c	55
	foO	90016329b8f53193eb562d53191d907b4e4a5529d087a2149469d09149c4ba24	

Table 1.1 – Hash results of of similar input strings for three different algorithms

they can be read by an attacker and used fraudulently elsewhere. Hence, best practices recommend to store the user password hashed cryptographically. A hash function is a one way mathematical function which converts a segment of data into a key.

$$F(x) = Key_x \tag{1.1}$$

This key has a fixed length which depend on the hash algorithm. In cryptography, hash functions have to verify more properties:

— it is infeasible to retrieve the original message from its hash,

— it is infeasible to modify a message without changing the hash,

— it is infeasible to find two different messages with the same hash.

In table 1.1, the input string "foo"is hashed using three different algorithms. The *MD5* algorithm produces a 32 hexadecimal digits hash, *SHA-1* 40 and *SHA-256* 64. Then one letter of the input string is modified and hashed. The resulting values are very distant to each other according to the Levenshtein distance. This distance measures the gap between to character streams in terms of actions to go from one to the other (add, delete, substitute). This property is known as the avalanche effect [40] [71]: one small modification, even a bit swap, of the input generates a avalanche of changes on the output hash. That property is essential for file transfer integrity over an insecure channel.

To protect a password, one not only needs to hash it but also to take care of the way it's done. To better understand why this is important, is seems appropriate to spot the threats when a hashed password is stolen. The hashing function ensures that it is not possible to directly recover the plain text password but the attacker can create a rainbow table [59]. A rainbow table is a database of hashes generated using a dictionary and some permutations. To find the original password given its hash, the attacker

simply looks for the hash in its database. The lookup is very quick as the table can be indexed by hashes to speed up queries.

In order to prevent the use of such tables, password should be hashed with a salt. The salt is a random string concatenated to the user password to produce the hash result. It breaks the rainbow table of an attacker as he will have to rebuild it using the correct salt. Having one salt per password makes the use of a pre-calculated table completely useless. Indeed, the attacker would have to build one table per password which is equivalent to brute forcing. Furthermore, the hashing function needs to be chosen carefully, obviously to avoid hash collision but also to ensure it takes a fair amount of time to generate a hash. Indeed when building a table of millions of passwords, the time to generate each hash is really important. The longer it takes to hash one password, the harder it is to rebuild a table. Today's standards advocate for the usage of the *SHA-256* and *SHA-512* algorithms.

After this short password storage presentation, the next paragraph explains how to verify the password between a client and a server.

Plain text

The first technique is pretty straightforward. The client sends its password to the server in plain text. The server hashes this chunk of data and compares the hash with the one stored for the given identity. If they match, the user is authenticated, otherwise he entered the wrong pass phrase. The benefit of this method is that it is really simple to implement.

Few weak points must be spotted though. First of all in most situations, the communication link is insecure: a third party can eavesdrop the data passing by that link. This might lead to password being stolen by an attacker. To address this issue, one can set up a secure channel between the client and the server to prevent eavesdropping. For web communications, *HTTPS* has become a popular protocol to protect the data on-the-wire. Another solution to protect the user password would be to hash it on the client side so it is not sent in plain text. It prevents an attacker from seeing the real password but makes replay attacks [67] [73] possible by directly using the hash as pass phrase.

The plain text method has the advantage of being dead simple but is only usable through secured links. Because this kind of links are hard to setup, other techniques have been built for instance by challenging the user

in order to verify its secret without sending it in an obvious way.

Challenge

In order to prevent password leaks on insecure channels, a challenge-response mechanism can be used. The user, instead of sending its password directly, first initiates an authentication session with the server giving him its identity. The server replies with a challenge that should be solved by the client. A trivial challenge implementation would be to use the user password but it would be as bad as the previous section scheme.

To prevent sending the plain text password, the server challenges the client by sending a random chunk of data. It then expects a response from the client. The response is obtained by hashing the challenge concatenated with the user password. The server compares the response with the expected value it has computed to know if the password is correct. This mechanism does not rely on sending the password directly to the server. Instead it uses the hash function property which says that it is infeasible to retrieve the original message from its hash to hide the secret.

Even though this technique prevents plain text passwords from being sent on-the-wire, it requires the server to store them in plain text format. Indeed to compute the expected response it has to use the real user password. A workaround uses hashed passwords instead of their plain text form. This way, the challenge response is computed using the password's hash. In this situation, the hash becomes the secret, hence the password, making the system as insecure as before.

Passwords are the simplest form of secrets in computer science. It requires the users to remember a set of characters in order to authenticate against a service. For security reasons, passwords should be hard to guess by humans and machines but in many situations, users are known to have weak passwords [33] [46]. Moreover they tend to re-use a password for multiple services leading to wider compromission if it is exposed.

They are still widely used because of their implementation simplicity and their adoption by all users. Next section presents a more robust authentication scheme bringing asymmetric cryptography into play.

1.1.3 Asymmetric cryptographic keys

Asymmetric keys, also known as public/private keys, are the strength of many security systems. *HTTPS* use them to exchange the encryption key between a client and the server, *SSH* on the other hand can perform a client authentication based on its public key. Both of these examples are based on the same property: data encrypted by a key can be decrypted using its counterpart.

Keys are generated by a generator with a random seed:

$$G(seed) = (K_{priv}, K_{pub}) \tag{1.2}$$

According to their names, the private key K_{priv} must be kept secret whereas the public key K_{pub} can be disclosed safely to others. Given an encryption algorithm A which takes a key and a data payload to encrypt it and its reverse form A' which takes a key and encrypted data to decrypt it, the following properties exist between the two keys:

$$A(K, data) = C \tag{1.3}$$

$$A'(K', C) = data \tag{1.4}$$

Here K can be replaced by either the private or public key and K' by its pair.

According to these characteristics, two scenarios can be implemented. First if K_{pub} is used to encrypt a chunk of data, only the owner of K_{priv} can decrypt it. This first scenario allows for example to send encrypted emails to a specific recipient: only the owner of the private key is able to decrypt and read the email's content. The second scenario uses the keys the other way around. Data are encrypted using K_{priv} so everybody can decrypt them using K_{pub}. In this scenario, the owner of K_{priv} can prove the authenticity of a message: indeed if the recipient of the message is able to decrypt it, then the message was issued by the correct sender. This second scenario can be leveraged to implement a signature system. The goal here is to provide a digital authenticity stamp in order for users to verify digital documents. The private key owner checksums the document in order to produce a hash H. He then encrypts this hash using its private key to produce the signature S:

$$A(K_{priv}, H) = S \tag{1.5}$$

This signature is appended to the document and sent. Now from a user point of view, in order to verify the document's authenticity, he also checksums the document and compare it with the decrypted signature:

$$A'(K_{pub}, S) = H \tag{1.6}$$

If the computed hash and the decrypted signature match, then the document was signed by the private key's owner. This system is used to sign email with *PGP* [75] as well as in the certificate chain of trust presented in next section.

With these use cases in mind, it becomes easy to authenticate the owner of a public key. Here the server has a public key and wants to ensure the user on the other end owns the corresponding private key. In order to verify that, the server challenges the user to decrypt a chunk of random data. These data are encrypted by the server using the user's public key and sent to him. In return, the client has to reply with the decrypted message. If the response is effectively the original challenge, it proves that the user owns the private key. To strengthen security, the operation can be done multiple times preventing the client from guessing are re-using older responses.

Asymmetric keys provide a safe way of authenticating users. Indeed because the secret is never sent between the client and the server, nobody can eavesdrop and steal from it. Moreover, asymmetric cryptography provides strong security on the encrypted messages preventing attackers to 1) decrypt a message, 2) fake a response. But this mechanism assumes that the server already has the user's public key and is able to match it with an identifier. In practice, the system uses client certificates in order to verify the user's identity and to retrieve its public key. This certificate along with the key pair are usually generated by the server at user registration.

Next section details how certificate works and demonstrates how they can be used to securely identify somebody.

1.1.4 Digital certificate

Previous section introduced the concept of asymmetric cryptography to securely authenticate a user. Still it assumed that the server and the client trust each other and know each other's keys. In real life such assumption can not be made and another mechanism must be added: digital certificates.

A certificate is an electronic document which contains information about a public key, its owner and a digital signature of an entity who has verified the certificate's content. The signer, called the *Certificate Authority* must be trusted by entities working with the certificates, here clients and the authentication server. To authenticate a user, one must verify that he owns the private key which is attached to the certificate's public key. This is easily implemented using the properties presented in last section.

The server must also have a certificate in order to ensure clients belong to the domain. Indeed it verifies that the client certificate was signed by the same CA as his certificate to tell if they are from the same infrastructure. If the verification fails, the user can not be authenticated. Hence care must be taken about the CA which signed the server certificate. Indeed if it is a public authority, all certificates signed by it will be valid for the server. In the context of a private network, it is an error to proceed this way because public authorities sign millions of certificates for thousands of entities. Rather the administrator should create a private CA which in turn signs every certificates created both for clients and the server. This way he can control the certificates he creates.

Last paragraph described *Public Key Infrastructure*. This system is in charge of creating, storing and distributing digital certificates within a specific entity's network. A difficult task of the PKI is to send signed certificate with its private key to the correct user. Indeed this step is critical as the private key should never be exposed to third parties. Secure channels is a way of transmitting such sensitive data over the network. Figure 1.2 presents a simple PKI with three clients, a Certificate Authority and one authentication server. Each entity has its own certificate describing its identity and public key in addition to a private key.

To authenticate a user based on its public certificate, a server can use the method described in last section: ask the client to sign a random challenge with its private key. Because the server has access to the client's public key inside its certificate, it becomes easy to verify a client has the

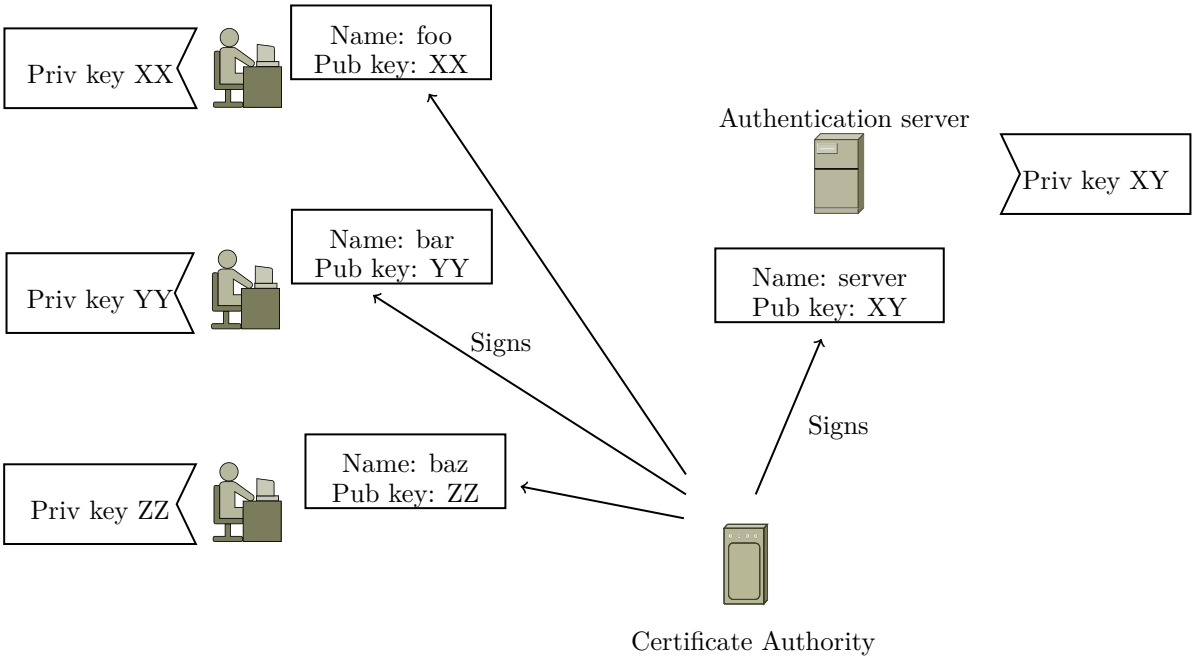


Figure 1.2 – A simple Public Key Infrastructure

private key associated with its certificate. Figure 1.3 describes a simple public key certificate authentication. When a client initiates a session, the server sends its certificate along with a verification request materialized by a random challenge. The client, after verifying the server's identity and the authority who signed its certificate replies with its own digital certificate. The response also contains the challenge signed by its private key. Finally the server can verify in turn the client's authority and the signature.

In order to perform the certificate based authentication, users have to configure a software on their device. Indeed because this step requires sending binary data to an authentication server, it can not be done by a user on a user interface. Rather the transaction is done in software from the user device to the authentication server. Depending on the software program, it could be difficult to configure this service and to give proper feedback to the user when an error occurs. Moreover the system's security is based upon the assumption that the private keys remain private. This requires proper configuration of the user device in order to prevent access to that keying material by unintended users and gives the user lots of responsibility on what he does on his computer to not be compromised.

The last two sections presented a secure way of authenticating users within a private network using asymmetric cryptography and Public Key

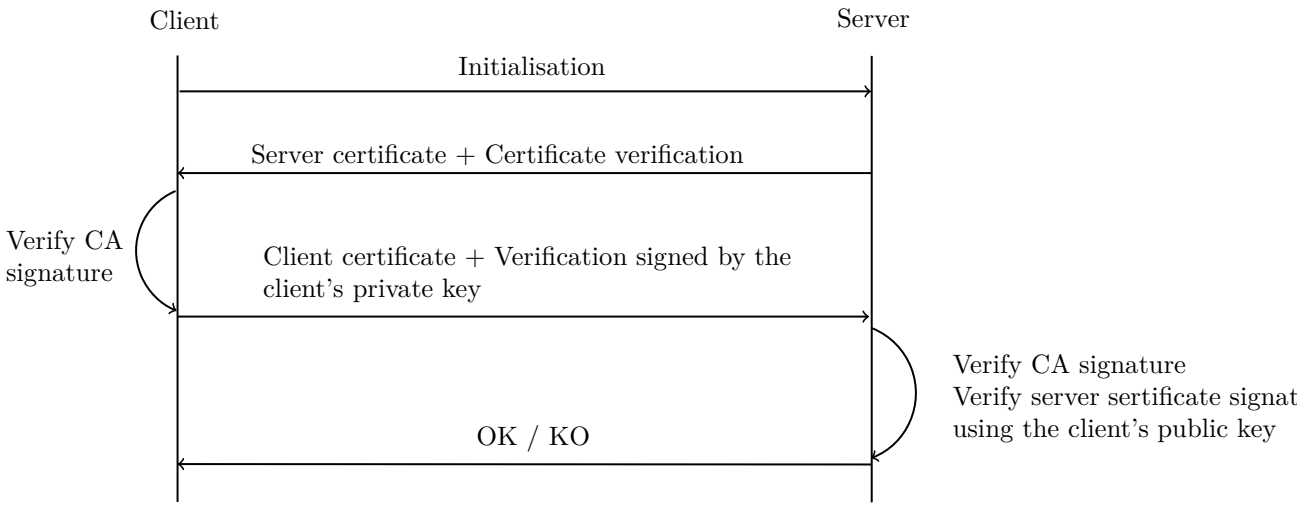


Figure 1.3 – Sequence diagram of a public key certificate based authentication

Infrastructure. It remains difficult to setup such a system because of the complexity of verifying user identity prior to sharing private information with them, configuring their device and giving them feedback when things go wrong. Next section presents how mobile phone operators manages to perform the same kind of authentication without user interaction nor visible configuration.

1.1.5 SIM

Mobile phone operators are subject to strict regulation rules regarding user authentication and control. In order to response to lawful interception requests from governmental agencies or to justify billing elements, they need to have solid evidence about the users' identity and their activity over time. On the other hand, users must have no interaction with the core system as they have no technical knowledge. In this context, mobile phone users are given a smart card known as the *Subscriber Identity Module* which performs all the authorization and authenticate process in behalf of the user.

The European Telecommunications Standards Institute has described in the *TS 11.11* [7] standard the features of the SIM card. It is a secure element storing information about the subscriber identity and keying material to authenticate it. Additionally, SIM cards may implement applications accessible from the mobile phone. The subscriber identity is known as the

International Mobile Subscriber Identity which is a global unique identifier. It holds information about the mobile phone operator as well as the subscriber which is useful when users roam outside their home operator's network. Operators welcoming the roaming users can then bill the correct entity for the usage of their infrastructure. Because SIM cards are physically protected, nobody can access private information directly. Rather it exposes encryption algorithm functions to the mobile device like a black box. When the mobile phone wishes to perform a cryptographic task using the SIM information, it simply calls the right function which gives it the result. This way, no sensitive information are exposed.

During the SIM customization process done by the mobile phone operator, a private key K_i is generated along with the IMSI number. They are both stored inside the card as well as inside the operator's database. This way both sides are aware of the private key and share the same information.

When a mobile phone tries to associate with the carrier's network, it sends an access request containing the IMSI number gathered from the SIM card. That information usually requires the user to enter a PIN code. Once the operator retrieved the K_i associated with the IMSI number, it generates a one time use random number $RAND$ and signs it with the K_i using the *A3* algorithm. This gives the first Signed Response called *SRES_1*. The $RAND$ number is sent to the mobile equipment which asks its SIM card to sign it. The SIM card signs using its K_i the random number and produces the second Signed Response called *SRES_2*. The mobile device sends it to the carrier network and waits for its response. The operator compares the *SRES_1* and *SRES_2* in order to know if the same K_i was used to sign $RAND$. If the two responses match, the mobile phone is authorized to access the operator network and the user's identity is confirmed.

Then in order to protect the confidentiality of the user's data, the communication link between its device and the carrier's network is encrypted. The encryption key K_c is derived from the $RAND$ again and K_i using the *A8* algorithm.

The security of the system lays in the fact that the K_i remains secret. However, researchers have found vulnerabilities in the cryptographic algorithms which can lead to the extraction of the K_i [66]. This might allow an attacker to duplicate a SIM card.

Carrier grade operators are able to provide secure and seamless access to

their networks without including the user in the configuration process. This challenging task is achieved with a complete control of the SIM fabrication process by the operator. All the infrastructure is built toward an complete abstraction from the user point of view. In the context of private network access, authenticating user with their SIM card is hard because one must be able to know the K_i. In real life, such infrastructure exists but delegates the authentication to the user's operator requiring a strong cooperation.

1.1.6 Summary

This section presented how users can be authenticated inside a network. The goal of authenticating them is to control who connects to the network. Indeed sensitive data might be accessible within the private LAN and users have to be recognized and authorized in order to access them.

To prove its identity, a user must provide information about the secret he holds. The nature of the secret depends on the authentication scheme. Multiple schemes were presented involving: passwords, challenges, certificates and SIM cards. Password based authentication is the least secure but also the most user-friendly. Indeed because this scheme is easy to implement, a wide range of services are using it, especially on web sites. Here, both the user and the authentication server is aware of the password.

More robust authentication schemes involving digital certificate or SIM leverage cryptographic principles to verify the user secret. They are both based on a private key which is used to sign some keying material. In the former case, the server verifies the signature using the client's public key included inside its digital certificate while in the latter case, the carrier operator knows the private key stored inside the SIM card because he customized it prior to commercialization. Despite the security enhancement they bring, these two methods are not easy to setup by individuals.

Next section focuses on network protocols which allow to manage authentications inside a network.

1.2 Authentication protocols for access control

In the previous section, multiple authentication methods were presented. It allowed the understanding of the different mechanisms and keying materials needed to verify a user's identity. This sections focuses on presenting the various network protocols to transport user authentications. Figure 1.4 describes a general view of a private network where users need to authenticate. From left to right, the user device communicates with a border controller which communicates with an authentication server. Typically, the border controller is in charge of controlling the user traffic by deciding whether to forward its traffic or not. It uses cross-layer information to build custom rules per device. This border controller uses the authentication server to decide if a user is authorized to access the network.

As a result, two kinds of protocols are presented in this section: from the user device to the border controller and from the border controller to the authentication servers.

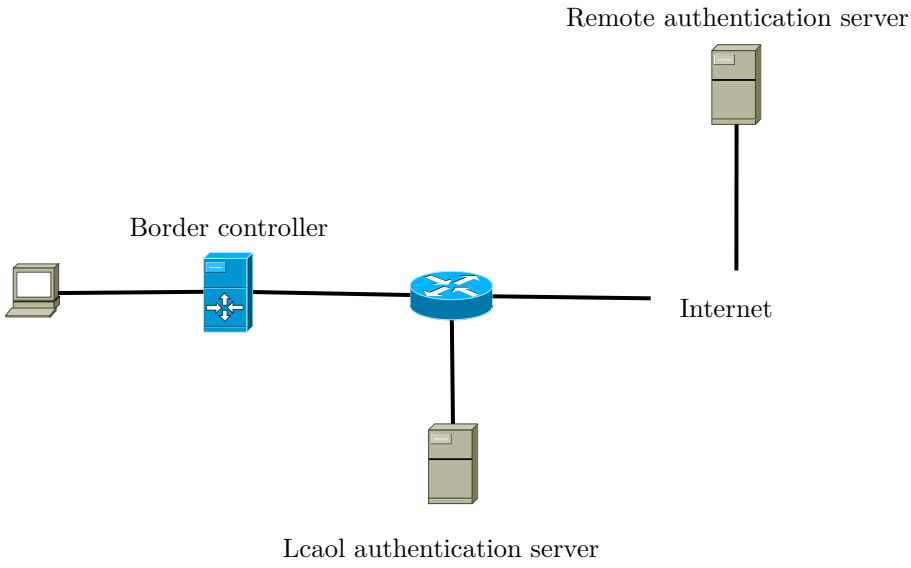


Figure 1.4 – Session border controller in a Local Area Network

1.2.1 Device to access network

This section presents the different communication protocols between the user device and the access network. The access network is embodied by an

access point which needs to validate that a user equipment is allowed to access the network.

Two protocols are presented here, the first one uses a user friendly web interface in order to communicate with the end-user whereas the second is a machine-to-machine protocol providing stronger security.

Web portal

This is the most user friendly protocol. The user interacts with the border controller using its web browser. The displayed web page is fully customizable and permits all kinds of contents to be embedded.

Unauthenticated equipments are authorized to use several network services in a degraded mode. To display a web page, the equipment has to at least have IP connectivity and a domain name resolver. The IP configuration is usually provided by an auto-discovery service such the *DHCP* protocol. The equipment requests an IP address by sending a packet on the *Ethernet* broadcast address `ff:ff:ff:ff:ff:ff`. The *DHCP* server looks for an available IP address in its address pool and replies to the user equipment. After the user equipment has acknowledged the IP address, the *DHCP* server stores its *MAC* address inside a lease. The lease has a limited life time after which the IP address becomes free again. Regarding domain names resolution, every device needs to be able to resolve any domain name so their web browser performs an *HTTP* request which is intercepted by the border controller. It should not fake the *DNS* response for legitimate domain names (where a record exists) because the device might store it inside a cache disrupting network connectivity after authentication. For domain names where no record is found, a fake *DNS* response can be made to force the browser to perform its request.

Various techniques can be implemented to intercept *HTTP* requests but they all have a common characteristic: impersonate the requested server to reply with either a redirection to the captive portal or directly send the captive portal. An implementation could consist in using the border controller's firewall to perform a destination *Network Address Translation* for the web traffic of unauthenticated user. This way, their traffic is redirected directly to the captive portal's web server. User devices think they are talking to the remote server they asked (e.g. `1.2.3.4`) but it's actually the captive portal who responds with an *HTTP* redirection.

Because the session border controller has a layer 2 connectivity with

the user device, cross-layer information can be retrieved via the Operating System API. The *Address Resolution Protocol* cache contains a MAC-IP mapping of all the devices on the network. Given the IP address of an HTTP request, the web server is able to gather a unique identifier of the device associated with it. This permits the web server to setup the correct firewalling rules when the user authenticates.

Captive portal is a good communication interface for end-users because they are used to face them on the Internet. Web pages can embed multimedia contents from images to geographic maps including videos, links and texts. These content types can be leveraged to monetize the Internet access by promoting local venues, proposing value added services or displaying ads to the end user.

Though it is an appealing solution, the only usable authentication method is pass phrase based because it's the only material a human being can remember and type on a computer. Section 1.1.2 spotted weaknesses in that scheme especially regarding the communication channel. By default, *HTTP* uses an insecure channel so it must not be used to transmit user passwords or sensitive data. Hopefully, a secure version of *HTTP* can be implemented over a *Transport Layer Security* [68] tunnel, this is commonly called *HTTPS*. The *TLS* tunnel is encrypts the data transiting in both directions and authenticates the server from the client side using server digital certificates (see section 1.1.4).

The authentication process consists in the user entering its user name and password inside an *HTML* form which is then sent onto the border controller's web server. This type of forms are very common on the Internet and non-technical users are used to fill them up to login on various websites. Leveraging client side storage with cookies or server cache memory, the server can remember the user information to automate future authentications. Captive portals are also a great tool to give comprehensive feedback to the user: what went wrong during his authentication, wrong password, exhausted time credit, what network services he is authorized to use or how long its session will last. Additionally, the feedback can be translated in multiple languages allowing a wide range of users to use the same captive portal. This last argument is crucial for public places welcoming visitors from all around the world.

Moreover, given the information provided inside the *HTTP* request header, the web portal can extract valuable data about the user device.

Indeed, web browsers usually send an *HTTP* attribute called the *User-Agent* which is filled with a character string describing the user device: name and version of the *Operating System*, browser name, hardware vendor, etc... With these information in hands, finer grained filtering can be done depending on the device the user is using. This is often referred as *Bring Your Own Device* where users can bring their personal computer at work. This feature allows to use different protocol filtering depending on the device the user is using. For example an administrator using its smart phone should not be able to access all the machines on the local network as it is not as trustworthy as a controlled computers from the company.

In summary, web captive portal is a great tool to communicate with non-technical users. It allows anybody to authenticate against a local database using a secret password. The portal enhance user experience by providing feedbacks and value added services. But captive portals suffer from weak authentication. Next section present a protocol aimed at securing network access which provide secure authentication.

802.1X

The *Institute of Electrical and Electronics Engineers* (IEEE) who standardized local area network protocols (IEEE 802) has defined a standard to control access to them. This standard is named IEEE 802.1X and uses the *Extensible Authentication Protocol* to transport keying materials needed to authenticate clients.

The *EAP* protocol is an authentication framework which defines messages to transport keying materials. It is a very generic protocol which can be used to transport any kind of authentication method. Each method presented in section 1.1 has its own RFC defining the parameters to be sent between a user device and the border controller. The RFCs list includes *EAP-TLS* for certificate authentication, *EAP-SIM* or *EAP-PAP* for password based authentication.

In the 802.1X standard, the border controllers are in charge of initiating *EAP* sessions with devices trying to associate with them. It is important to emphasize that IEEE 802 protocols are low level protocols. As a result, *EAP* messages are directly sent on the physical link encapsulated inside the corresponding protocol. As an example, 802.1X can be implemented over Wi-Fi, a device associates with the access-point which requires an authenti-

cation. The device and the access-point then transmit *EAP* messages over Wi-Fi frames directly until the end of the *EAP* session is reached. In the end, an accept or a reject decision is taken by the access-point letting or refusing access to the device. As *EAP* messages transport keying materials to authenticated the user device, they need to be forwarded to an authentication server who is able to perform the correct authentication process. A common solution is to encapsulate *EAP* packets inside the *RADIUS* protocol to route the packets through a layer 3 network. *RADIUS* is detailed on the next section.

Because 802.1X is implemented directly over the link layer, unauthorized devices have no access to the core network. For instance they can not retrieve an *IP* address from the *DHCP* server nor query the domain name server. This is a clear improvement regarding security compared to the previous section. Here all the traffic passing through the network comes from authorized and authenticated devices. Figure 1.5 presents a simple 802.1X authentication between a user device and a border controller. The device exchanges *EAP* messages through a 802.1 protocol (e.g. Wi-Fi, Ethernet) with a border controller. The controller encapsulates the messages inside *RADIUS* packets and forward them to its authentication server. When the authentication succeeds, the device is authorized to access the *LAN*.

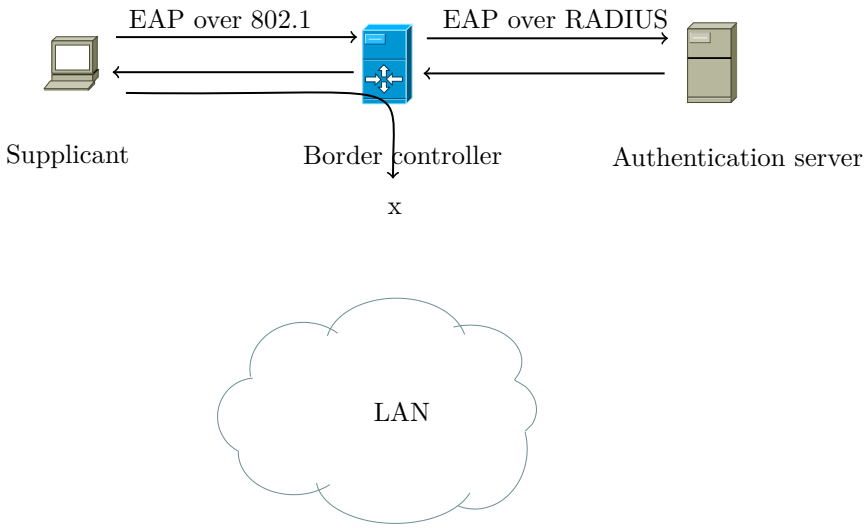


Figure 1.5 – Unauthenticated device trying to access the network through *802.1X*

In the present situation, only the user device MAC address is available to the border controller. This information alone is enough to build proper firewalling rules to allow access to single devices. When encapsulat-

ing *EAP* messages in *RADIUS* packets, the session border controller adds a set of information about itself and the device being authenticated. Although no standard exists about what information are mandatory or not, the MAC address of both equipments, the border controller's IP address or the SSID/VLAN assigned to the device are examples of common information found in such requests. These cross-layer information enables finer grained filtering on the authentication server to identify the border controller on which the user is connected, derive its geographic location or simply log the device's MAC address of the user.

As stated before, 802.1X is a machine-to-machine protocol in the sense that it requires two machines to transfer binary data over a network protocol. On the client side, a software called the *supplicant* implements the client's part. On the other side, the border controller also has a specific software which implements its part. Configuring supplicants can be hard, indeed depending on the authentication method, it can require certificates, private keys and various identities to be configured (tunneled authentications [36] [12]). Because each software is built differently, there is no standard method to do that. It is simply not possible for non-technical users to configure this kind of software as they do not have technical background on authentication or network access. Moreover, despite proper configuration of the supplicant, feedback can be sloppy in case of errors. Indeed authentication servers usually return error codes, if any, which are hard to understand for users.

802.1X is a standard which provides security of user-friendliness. Using secure authentication schemes, it gives strong security to a local area network. Compared to captive web portal, the attack surface is drastically reduced because unauthenticated devices have no access to the network. Moreover the use of cryptographic algorithm in the authentication process gives a better level of trust on the users accessing the network. For these reasons, 802.1X is a perfect solution for enterprise networks where computers are controlled by the company. Indeed users do not configure their computer hence the lack of user-friendliness is not an issue (given that the setup works).

After this presentation of protocols to communicate between the user device and the border controller, next section presents protocols between the border controller and the authentication server.

1.2.2 Authenticator to authentication server

The intent of the section is not to present an exhaustive list of protocols between an authenticator and an authentication server, but rather to outline the important ones. This section starts with *RADIUS* which has been extensively used in access networks for the past twenty years.

RADIUS

The *Remote Authentication Dial In User Service* protocol (RADIUS) is a network protocol developed by Livingston Enterprises, Inc. in 1991 later standardized by the IETF. It is described in RCF 2865 [19]. This protocol is intended to manage network access from a centralized point. Access is managed using *Authorization, Authentication and Accounting* transactions. It uses *UDP* as transport protocol to communicate between different entities.

The protocol defines a list of packet types to be used to request access, exchange challenges or grant/deny access. Each packet contains a list of attribute value pairs. RFC defines a lot of attributes including user name, user password, allows vendor specific attributes to be defined using custom dictionaries.

When the border controller needs to perform an access request, either coming from its web server or from an 801.1X session, it sends a RADIUS *Access-Request* to the authentication server containing the user identity and other parameters about itself. If there is enough information in the *Access-Request* to authenticate the user (e.g. a plain text password based authentication), the server replies with a yes/no packet respectively *Access-Accept* and *Access-Reject*. When the authentication method requires more than one step, for instance password challenge seen in section 1.1.2 or client certificate from section 1.1.4, the authentication server replies with an *Access-Challenge*. The border controller is then forced to respond correctly to the challenges until the authentication server finally sends an *Access-Accept* or *Access-Reject* packet.

When a user is authorized to access the network, the border controller can optionally send an accounting start request to provide the server with information about the user session. Typically, this request holds the accounting session identifier that will be sent again at the end of the session. The border controller is then supposed to count the amount of time, packets

and data consumed during the session so they can be sent when the user disconnects. When this happens, an accounting stop request telling the server the user session has ended is sent. This request contains accounting data as well as the reason why the session has terminated. During users' session, the border controller can send interim requests to inform the server about the accounting information on the runtime. These packets are sent periodically every few minutes. Care must be taken not to overwhelm the *RADIUS* server with too many requests. Leveraging the *RADIUS* interim, a server can detect terminated sessions even if the accounting stop packet has been lost. Indeed whenever a session is no longer updated by interim requests, one can assume something went wrong and that the sessions can be closed. Moreover, user session information can be updated by the server following an interim request using the *Change of Authorization* (CoA) packet. This mechanism takes advantage of a *NAT* property where a packet emitted in response to a request will correctly be delivered to the sender. If a packet is sent by a server to a client's public *IP* without prior request, the router gateway would have no rule to forward it to the right destination. Hence in response to an interim request, the *RADIUS* server can reply with a *CoA* response containing new attributes to apply to the user session: bandwidth, session maximum duration, class of filtering or even ordering a disconnection.

The *RADIUS* protocol makes an extensive use of realms to route requests to the correct home server. Indeed, *RADIUS* is built upon the idea that users can authenticate against their service provider from a foreign location. *RADIUS* servers are able to behave like proxies, relaying requests and responses. Figure 1.6 presents a chain of *RADIUS* servers. Each server treats incoming requests in the following manner:

1. it extracts, based on its configuration, the realm from the *User-Name* attribute,
2. it looks for the home server corresponding to the realm value,
3. if it's a remote server, it proxies the request to it, if it's the local server, it processes the request by itself.

The way a server handles a request is completely configuration dependent. This implies that for a proxy chain to correctly route requests, each server must be correctly configured. Realms, as presented in section 1.1.1, are delimited in the login by a special set of characters. The

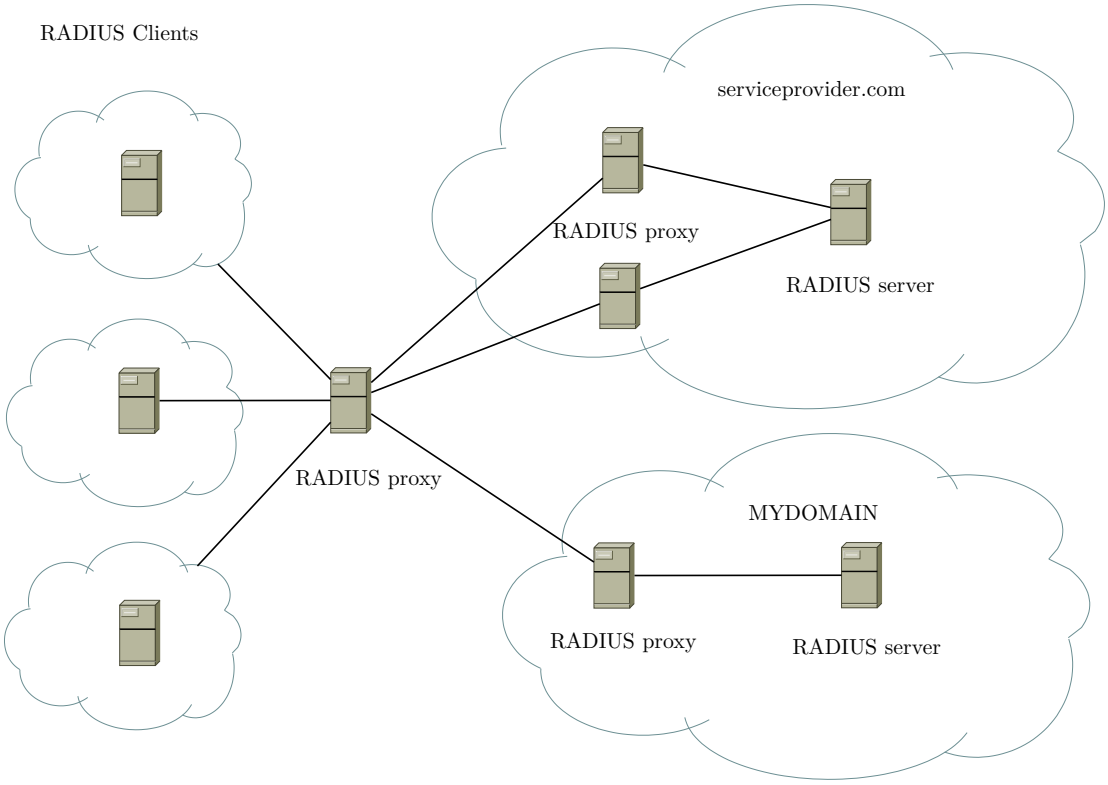


Figure 1.6 – Chaining of *RADIUS* proxies which route requests to the right service provider

first example was the email address where the realm was located after the '@' character but other formats, for instance the Windows domain, place the realm in prefix. As a result, realm formats has to be configured inside the *RADIUS* server. Describing a format essentially consists of telling whether the realm is a prefix or a suffix and what is the delimiter. The order in which realms are extracted is also really important. Let's take a user name which potentially contains two realms: *MYDOMAIN*\\john.doe@**serviceprovider.com**. Depending on the order, the server might extract respectively the realm *MYDOMAIN* or **serviceprovider.com** and the user name john.doe@**serviceprovider.com** or *MYDOMAIN*\\john.doe. As the realm tells the server where to send the request, it is important that the matching is done in the right order. After finding the correct home server to proxy the request to, the current server has the possibility to modify the *User-Name* attribute to remove the realm section, the user name is now *stripped*. The stripping hides the local realm to the remote server, for instance in the previous example, *MYDOMAIN* corresponds to a local Windows domain on which the user is connected, it should not be treated as part of the user name by the home server hence it

has to be stripped prior to proxying the request. Though convenient, not all servers need to strip the user name, some might only route the request to another server without matching a local realm.

RADIUS has been designed during a time when data confidentiality and security was not a trending topic on the network community. It explains why it lacks common encryption features present in most authentication protocols nowadays. In practice, the only security feature present in *RADIUS* is the use of a shared secret between two servers. This secret is used to hash the user password so it is not sent in plain text. Besides the fact that it prevents password eavesdropping, it also ensures that the two servers know each other. On the one hand, this prevents unauthorized access to a server (hence to a user database) but on the other hand, this is an obstacle to cooperation between actors. Indeed, for a network access provider who wants to cooperate with different service providers, both him and the service provider need to accordingly configure their servers and test everything works as expected.

Moreover, the use of *UDP* gives no insurance about the arrival of packets to the other end which is one of the biggest *RADIUS* weakness. Servers can not reliably behave to packet loss which is problematic for *AAA* protocol. The reason why *TCP* was not chosen is because it was meant to be used between networks with high latency. Back in the days, *TCP* performed very poorly in such circumstances hence *UDP* has been chosen.

Coming back to security, *RADIUS* uses *MD5* to hash the user password concatenated with the shared secret. This algorithm suffers from several weaknesses which makes it insecure to use today [72] [32]. Such hashes are rather easy to break mainly because of the collision rate of *MD5*. Furthermore, this only protects the password, not the rest of the data. This is a major issue as sensitive data about the user or the network are exchanged in *RADIUS* packets. Thus, it is good practice to encrypt *RADIUS* traffic when it's sent on an untrusted network (e.g. the Internet). The industry has adopted *ipsec* as a good solution to implement this encryption layer. It provides *IP* payload encryption and integrity check with the benefit of being transparent for upper layer protocols.

To cope with *RADIUS* weaknesses, its successor, *DIAMETER* has been designed. It uses *TCP* or *SCTP* as transport layer and advises to use *TLS* encryption at the socket layer. It can be backward compatible with *RADIUS* but is aimed to perform better than its ancestor. Though it has

appealing features built in, this newer protocol is still not widely deployed, only carrier grade operators have made a use of it by now.

Next section presents a protocol which is not stricto sensus a network protocol but can be leveraged to implement a user database in addition to user authentication.

Lightweight Directory Access Protocol

LDAP is an applicative protocol to access and manage information directory services over the network. It is specified by the IETF as multiple RFCs. The latest one defines the Version 3 in the RFC 4511 [44]. *LDAP* uses either *TCP* or *UDP* as transport layer on port 389 with no encryption, or port 636 with *TLS* encryption.

Information directories store data according to their directory schema. This schema defines the data structure with a number of elements per object:

— Attribute syntax - defines what information can be stored in an attribute
— Matching rules - defines how to compare the attribute values
— Object classes - defines a set of required and optional attributes identified by a unique name

Data is stored in the entry's attributes. Each entry has at least an *Object class* which tells what kind of object it represents and how clients may interact with them. Clients can access the server schema to learn about the elements' structure as well as the hierarchy of entries. Entries are identified by a distinguished name called *dn*, it is neither an attribute nor part of the entry. The *dn* contains a common name (e.g. John Doe) plus the *dn* of its parent entry.

For example, a user can be represented by the **person** object class. Its common name is "John Doe"and it is part of the *example.com* provider. Hence its *dn* can be represented as:

```
dn: cn=John Doe,dc=example,dc=com
```

The **person** class requires no attribute itself but inherits from the **top** object class, a special abstract class, forcing the definition of the *object class* attribute. The **person** object class defines optional attributes including the *userPassword*, *telephoneNumber* or *description*.

Clients access the directory server using a set of operations: *add*, *search*, *delete*, *modify*, *bind*... When a session starts, the *bind* operation allows the

user to authenticate against the directory. The *simple* bind uses the user's *dn* as well as its password in plain text to check if the *userPassword* entry matches. Such operation should be encrypted to avoid eavesdropping. A wider range of authentication mechanisms is provided by the *Simple Authentication and Security Layer* bind such as *Kerberos* [41] authentication or *TLS* authentication using certificates. Once the client is bound to the directory, he has access to a subtree corresponding to his identity. Furthermore, he gains the rights to use (or not) other operations.

Leveraging the bind mechanism in addition to the information structure makes LDAP a great tool to manage users in a guest access environment. After users being authenticated against the directory, they have only access to their information. Furthermore, the network topology including incoming networks, zone definition, network services can be stored in that directory allowing the retrieval of key information for each user.

1.2.3 Summary

The combination of protocols presented on the last section allows to implement all kinds of network access controls. Indeed based on one's needs, user-friendly setup with value added services can be implemented using a captive web portal or on the other side, tight access control can be implemented using 802.1X and *RADIUS*. Leveraging the capacity of every protocols and combining them together permit to implement custom filtering and build appropriate architecture to answer any kinds of needs.

The authentication process aims at binding an identity to a network equipment in order to grant it network access. This process is possible here because all the equipments belong to the same private network. As a result, border controllers are able to identify uniquely user devices using OS API. It is important to acknowledge that these API are platform dependent and vary from one OS to another. In chapter 2 and chapter 3, this lemma is broken which complicates the architecture.

In the present state of the presentation, one can store user identities in databases, control user identity via multiple authentication methods and monitor user sessions over time. The missing piece to have a complete network access control solution is flow control. Next section presents multiple techniques to identify and filter user activity on the network and how they infer or not with user privacy.

1.3 Flow control

This section treats the control of the user network activity. A user profile is assigned to each user after being authenticated. It defines all the information about accessible resources inside or outside the network, authorized services and session constraints (bandwidth, time limitation). The different storage techniques presented in the previous section can be used to store the profiles' information.

In order to correctly understand how network flows can be controlled, it is important to understand network protocols in the first place. Next section makes a quick introduction about protocols' hierarchy.

1.3.1 Hierarchy of protocols

To exchange data over the network, applications extensively use communication protocols because machines need very structured data representation to understand each other. A parallel can be made with humans which communicate using the natural language except that machines need way simpler language then humans. Network protocols are classified into layers in the *OSI* model [6]. Figure 1.7 presents the seven layers of the OSI model. Each layer has its own purpose: from transmitting frames on a physical medium (layer 2) to sending application data (layer 7) including transport (layer 4) and network (layer 3). Figure 1.8 outlines that each layer works in pair with another machine. In the OSI model there is theoretically no link between layers such that any protocol can be used in each layer as long as the other side uses the same protocol. In practice though, the OSI model is not implemented in a strict manner because many protocols use information from underlaying protocols. For instance *TCP* uses *IP* addresses from the *IP* layer to compute its checksums and identify sessions. In the figure, the two machines on the edges use *TCP* as layer 4 protocol and *Ethernet* as layer 2 protocol whereas the routers in the middle use *PPP* [49]. The routers only treat lower layers to forward the packets to their destination.

Coming back to applicative protocols, they usually use a specific transport protocol: mostly *TCP* or *UDP*. *TCP* stands for *Transmission Control Protocol* and ensures data are received by the other side, in the right order and unaltered. A more detailed description of *TCP* is made in the third chapter 3.4.1 of this thesis. *UDP* in the other hand, for *User Datagram*

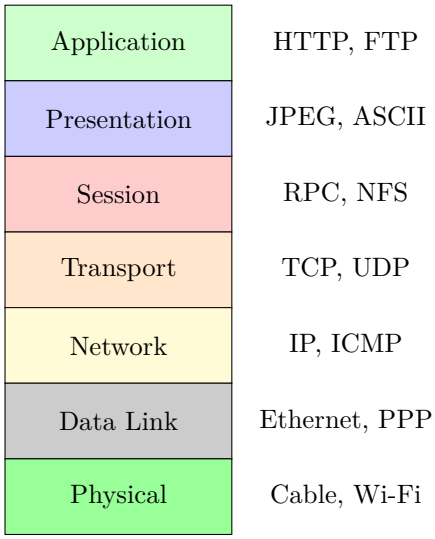


Figure 1.7 – Representation of the *OSI* stack

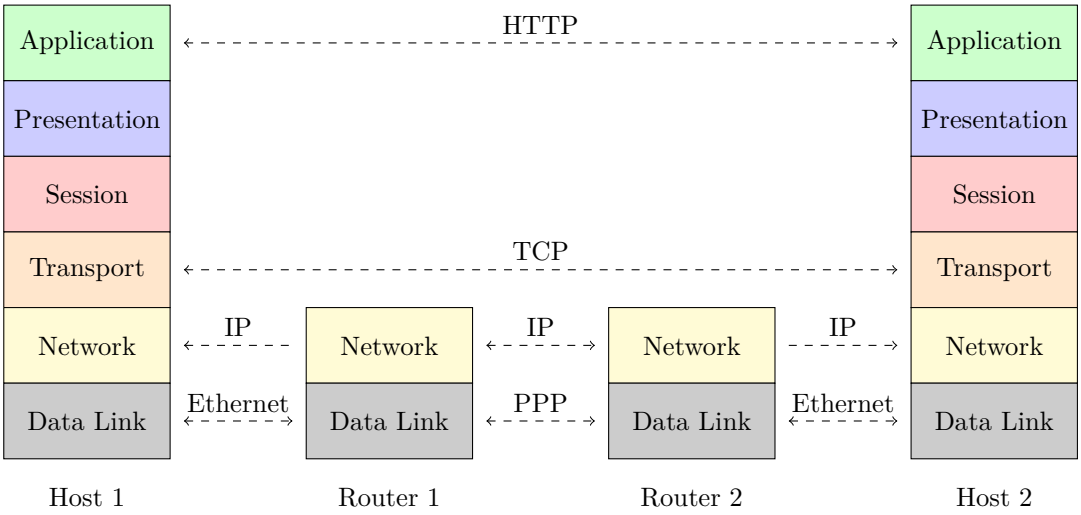


Figure 1.8 – Network stacks collaboration

Protocol is a transport protocol which does not check for packet loss, or unordered packets decreasing the overhead of *TCP* regarding latency and jig. Both protocols have a common feature, they both use port numbers to multiplex communications between hosts. Each packet has a source and a destination port number which identify the application on each side. It is very common for the client application to randomize its source port number but the server side application has to bind to a specific port. The *Internet Assigned Numbers Authority* (IANA) has defined a list of standard ports to use for well-known applications. As an example, *HTTP* is bound to destination port 80 on *TCP* where as the *Domain Name Service* (DNS) uses *UDP* on port 53.

The objective of the remainder of this section is to expose two techniques to classify network traffic, describe how to control the *HTTP* resources accessed by users and finally explain how to intercept and store traffic meta data for lawful obligation.

1.3.2 Basic firewalling

This section's preamble, introduced the *IANA* port numbering convention [3] to map applicative protocols onto a specific transport protocol port. A simplistic network traffic classification approach is to match the packets' port number. For each packet passing through the firewall, the destination respectively source port is identified for packets being received respectively sent by the server. It corresponds to the applicative protocol's standard port. Figure 1.9 presents two clients connected to the same server with *TCP*. Both client connections pass through the same firewall. Clients choose a source port number randomly and use the same destination port, here 80 for *HTTP*. The firewall uses the destination port to identify the applicative protocol being transported. This technique makes the assumption that the *IANA* port numbering convention is followed by users in the network.

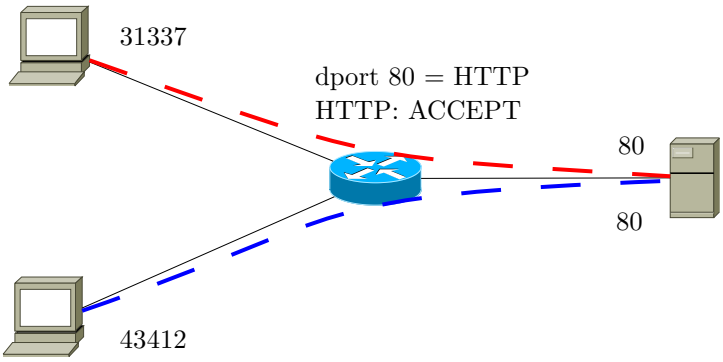


Figure 1.9 – Basic firewalling rule based on *TCP* destination port

As this is true in most cases, it works pretty well. The necessary computing power is very low, all the firewall needs to do is match a number in a fixed position of each packets [1]. As a result, the majority of firewall deployments use this technique to classify network traffic. It is important to stress that the firewall stays away from the content of the packets which has two effects: first it prevents intrusion in the user's privacy as packets content

1. The port number offset is fixed in transport protocols but lower protocols might have variable length.

can hold sensitive data ; but on the other hand, it lacks the ability to gather valuable data about the traffic content (e.g. application headers). The limit between a packet's header and its content can be tricky though. Strictly speaking, each network protocol has a header followed by a payload, its content. Hence depending on the layer, the content changes. For example at the IP layer, the header contains IP addresses but for the Ethernet protocol, they are part of the payload ! In this thesis, the header is composed by all the network protocols headers: link, network and transport. The rest is treated as applicative data.

Getting back to flow filtering, the main problem of only looking at port numbers is that clients and servers can use applicative protocols on non-standard ports as long as they agree with each other. This can lead to filtering evasion by users in the network because they can use a restricted protocol on the port instead of an authorized one. For instance, in most guest networks the *HTTP* protocol is guaranteed to be available but *VPN* protocols might not. An ill-disposed user could set up his *VPN* server to use the port 80 and connect to it from the guest network without any problem because the firewall will treat the *VPN* traffic as if it was *HTTP* traffic. In addition, *VPN*s and tunneling protocols permit to transport data, even lower layer protocols, inside them leading to a complete bypass of the firewalling rules in the event where the user routes all his traffic inside.

To prevent such filtering bypass, more advanced techniques can be deployed, the next section presents one of them.

1.3.3 Deep packet inspection

To address the previous section's limits about network service classification, more efficient solutions have arisen. They are known as *Deep Packet Inspection* techniques (DPI). The general idea is to look into the packets' content rather than just their headers. It's a very challenging task for multiple reasons. First the data in the packets' payload might be anything, from a standard protocol such as *HTTP* or *DNS* to unorganized plain text data including encrypted traffic. Although useful data is usually located in the protocols header like in lower layer protocols, applicative protocols headers are not replicated in every packets. Furthermore, there is no guaranty on the header location inside a packets flow, for instance underlaying protocols might require to initiate a connection prior to sending applica-

tive data. As a result, extracting all the necessary data to identify the applicative protocol requires a number of packets to be collected.

In addition to this complexity, the protocol classification, even with enough data in hands, is hard. Indeed there is a great protocol diversity and a huge number of them which requires a fair amount of computation to parse and identify what protocol is being used. Because this has to be done for every transactions between a client and a server, the computing power needs to increase with the traffic growth. As a result, *DPI* solutions are mostly deployed in data centers where computing power is sufficient.

In the context of network access control, *DPI* solutions are very powerful tools because they permit to filter user traffic on a service based. This prevents for instance the filtering evasions presented before where a tunneling protocol where used on a non-standard port number. Furthermore, when traffic is encrypted and a server-side authentication is performed by the client (e.g. *HTTPS*), it is feasible to extract the server's name from its certificate. This can be leveraged to identify the website being accessed by the client despite the fact that all the traffic is encrypted. It is then possible to know that a user accessed popular websites such as Facebook, Youtube or Google and even forbid him the access.

It is pretty clear from the description given in this section that *DPI* solutions are intrusive in regards to the traffic content. For real users it implies violating their privacy by looking at the resources they access and the content of their communications. For machines, *DPI* can be used to eavesdrop on sensitive data being exchanged between different locations. All these issues raise great concerns on the Internet because *DPI* can be used both the for the good and the evil with little control over what is being done.

1.3.4 URLs filtering

In various situations, users might be disallowed to access some websites: pornography for children, games and videos for employees of a company or phishing websites for any kind of users. To prevent users from accessing such websites, a middle box needs to intercept the web traffic and decides whether he is allowed to access it.

To intercept the web traffic, the middle box implements what is commonly called a *transparent web proxy*. As its name states, user web browser will not detect that the connections it makes with web servers are being

intercepted and, maybe, modified by the proxy. It is important to note that this does not concern encrypted traffic such as *HTTPS* connection where transparent proxies would break the chain of trust between the client and the server. 1.10 demonstrates how *HTTP* packets are intercepted by the middle box and relayed to the web server. The idea behind this is to intercept the *TCP* session so that the client talks directly to the middle box thinking it's the server he asked for. Then when the proxy receives the *HTTP* request from the client's browser, it establishes a *TCP* connection with the real web server and sends the request to it. The returning path is trivial as it is a copy of the sending but in reverse.

With the *HTTP* request in hand, the requested URL is easily extracted. The proxy can then look up in its database to decide, given the user profile derived from the user IP address, if it should deny access to the resource. This can be implemented using open source solutions such as *squid* plus *squidguard* [4] [5] with an external helper program to derive the user profile from a given IP address.

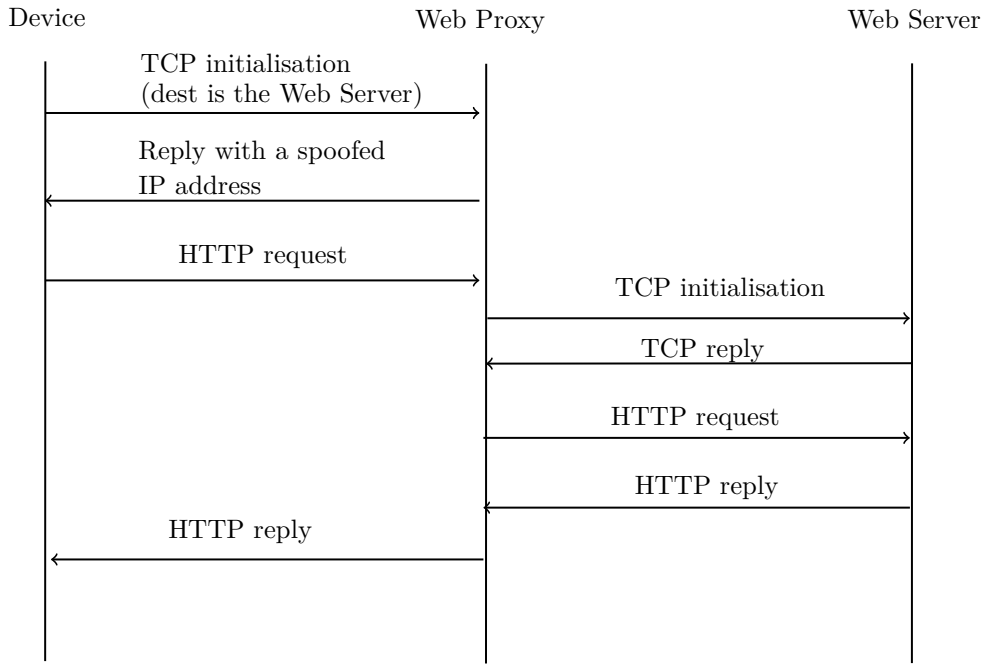


Figure 1.10 – Web proxy interception

URL filtering is a powerful tool to control user activity on the web. Despite preventing unwilling access to websites, it permits to restrict categories of websites which are prohibited in certain places and countries. Speaking of which, next section discusses about lawful obligation in general.

1.3.5 Lawful obligation

In many countries, Internet access owners are liable for its usage. The European Parliament has voted a directive in 2006 which forces telecommunication actors to store user logs from six months to two years. Though this directive was canceled in 2014, many European countries already transposed it in their own right. It is unsure for the moment if these countries will go back or not on that subject.

Since the law requires data retention in order to identify a posteriori user activities within any networks, middle boxes have to record user activity on the runtime. The law is evasive regarding the necessary data to record. Basically it has to be possible to identify the source of a communication, its destination, the date and duration, its type and the machine used to communicate. From a technical point of view one can interpret this as storing the user's equipment IP and/or MAC addresses along with the user identity, the server being accessed as well as the transport port number (i.e. service).

The storage of all collected data requires a fair amount of disk space as well as computing power. Indeed in sites with a high user activity, gigabytes of data are generated every months. Furthermore, they have to be replicated in case of a disk failure. Taking into account the retention duration, it is a likely event. Adding extra equipments to store the user logs is an extra cost only affordable by owners who absolutely require it. Most small venues owners do not have the money to buy these kinds of hardware.

Another aspect of this lawful obligation is that it is fairly intrusive in regard to user privacy. Indeed, user data are being stored by the Wi-Fi provider in a rather obscure way since nobody controls how data are being stored. Most of the time, the network administrator has access to all data including visited URLs, which might contain compromising and sensitive data. Of course users have to be aware that their data are being recording and providers are required to inform their public about the type of data the store and they duration of the storage.

Finally, the benefits of these obligations are somehow questionable. The objective is to identify a user on the Internet in the event of a law violation. But as described in section 1.1.1, an identifier might not be sufficient to match a user identity, plus the user identity is not always known by the provider. Hence, he will record user data without the ability to identify the

users, making this plan of action useless.

1.4 Summary

This fist chapter has been the occasion to present access control in private networks. It outlined the importance of user authentication to perform custom network filtering. User identity is verified by an authentication server which ensures the user possesses the right secret. Multiple authentication methods were presented providing different level of security. The more secure they are, the lest user-friendly they get. This trade-off is common in security. To transport the authentication materials, multiple protocols were presented. Some of them, RADIUS for example, permit to route authentication requests through a multitude of servers. The routing extensively uses realm names inside the request to choose whether to forward it to another server or to perform the authentication locally.

Then when the authentication succeed, the user identity is mapped with its device. This allows to build firewalling rules to authorize and filter the user traffic. A couple of techniques were presented to control user traffic: the first one only inspects up to the transport layer of packets' headers to classify the traffic and take a decision whether to accept or deny it. The second one takes a deeper look inside the packets' content to match the applicative protocol being carried. Additionally, meta-data can be stored by the network gateway in order to reply to lawful authority's requests. These meta-data are valuable because they allow to identify the origin of a network activity on the Internet.

Given the knowledge acquired during this network access control state of the art, it is clear that each piece uses a specific network layer. Packet inspection and firewalling use low layer information, message routing and secure channel mid layer and identity management plus authentication the application layer. This demonstrates the need of a cross-layer approach to build a network access control solution. Indeed, every pieces need information from others: firewalling is dependent on the user's identity, authentication depends on the user location (based on its network device address) and authentication messages transport network information.

In the present situation, each actor is able to retrieve cross-layer information either from the messaging protocol (e.g. RADIUS) or directly from its Operating System's API. As a result, some equipments have to

be hosted within the same local network. Obviously the session border controller is one of them because it is in charge of filtering user traffic but the captive portal is another one. Indeed it has no other option to gather cross-layer data but from the local Operating System's database. Having an access control management instance per network is expensive and hard to maintain. Mutualizing this entity between multiple networks is a clear improvement. Next chapter presents a mutualized network access controller, hosted in the Cloud. It outlines the technical challenges brought by this new architecture in terms of cross-layer information sharing.

Chapter 2

A mutualized approach

This second chapter presents the evolution of network access control with the rise of Cloud computing. Given the benefits of hosting virtual machines inside a data center in terms of storage capacity, computing power, bandwidth, replication and high availability, it is appealing to consider having a network controller there. Moreover, some Wi-Fi access points are now able to interact with a remote captive portal allowing to decouple the controller from the border access gateway. Great benefits can be drawn from such architecture because it removes the need of having a network controller per-site by mutualizing it in the Cloud.

Although it brings many benefits, this architecture brings another set of challenges. This architecture has to overcome the fundamental cross-layer problems, but it also has to realise this in a distributed environment. Given the potential of this architecture from an industrial point of view, it was appealing for the company to have a concrete implementation of this proposal rapidly. As a result, this chapter presents both the challenges brought by the distributed environment in regards with the cross-layer problems and the practical implementation done to overcome these challenges inside the Ucopia product. It is important to note that this implementation is an inherent part of the Ph.D because it allowed to face various problems when hosting the access network controller remotely.

The chapter is structured around four sections: it starts with a brief presentation of the motivations in section 2.1, both pecuniary and the potential to scale. Then the architecture is detailed in section 2.2 with a focus on the technical challenges. The third section 2.3 deals with the implementation of the controller and how technical challenges have been overcome. Finally the last section 2.4 discuss the limitations of this solution and how

they can be addressed.

2.1 Motivations

The network access control market is strongly segmented. This results in a situation where there is on the one hand clients needing to control tens of thousands of simultaneous users and willing to afford it. And on the other hand clients who only need to sporadically control the access on their Wi-Fi hotspot and are not willing to pay for an expensive solution. In between there is clients wanting to equip a large number of distant sites and have a unique control interface to manage all their hotspots. While monolithic controllers, such as the *Ucopia* solution presented in the first chapter 1.4, are perfect to control a large amount of users on the same location, they are too expensive for very small venues and can not scale with sites multiplication. Indeed as the controller holds the role of border gateway, one needs to setup a controller per site which rapidly becomes way too expensive to configure and constantly operate.

To address this market segment, it is crucial either to drastically reduce the controller's cost which seems difficult simply because of hardware costs, or to mutualize the controller among multiple clients. The latter proposition is interesting in the current context. Despite virtualization progress, having multiple virtual machines in data centers is still quite expensive but because clients share the same hardware, the more they are, the less it costs. Plus data centers provide platform flexibility permitting to adapt the hardware needs, in terms of bandwidth and computing power, on demand. The problem with concrete hardware is that it needs to have enough capacity to hold its maximum charge though it might be idled the rest of the time (e.g. . Amazon's black Friday).

Having a mutualized controller hosted in a data center modifies the cost distribution between Opex and Capex, indeed it is no longer required to buy the hardware resulting in almost no Capex but it increases the Opex because the hardware is rented. While in the short term virtual machine hosting is cheaper than concrete hardware, the expenses balance overtime hence to make a Cloud application profitable, it's a good idea to share it between multiple clients. This splits the Opex among all the clients reducing the cost of the solution.

Additionally the on-site environment may not be appropriate to host

computer equipments. Heat, humidity and power outage... are potential causes of damage to the on-site controller. Data centers are specifically designed to be a safe environment to run computers. Similarly, real hardware suffer from failures, disks, memory, or network cards may break leaving the whole system inoperable. To provide high availability, one needs to have spare controllers on-site in order to take over in case of failure, which multiply the solution's cost. Data centers natively address this by providing hot virtual machine migration and hardware redundancy.

Despite all the advantages of data center hosting for the network controller, an on-premise border controller is still required to physically control user traffic. Nowadays, Wi-Fi access-points are able to play this role. As they were already vital in previous architectures, it is very convenient to reuse them here with additional features. Moreover, this kind of lightweight equipments is more resilient, mainly because they do not have any device that moves (e.g. hard drives), hence better suited to be hosted on the premise environment. The proposed architecture intends to integrate a wide range of Wi-Fi vendors hardware already available on the market. The remote controller has to be implemented to correctly interact with each vendor's hardware.

Last but not least, the proposed architecture does not rely on network tunnels to forward user traffic to a central controller. It prevents adding packet delays, single points of failure and reducing bandwidth [14]. Authenticated user traffic is directly routed onto the Internet using the local *ADSL* or optic fiber access. The overall architecture capacity grows with the number of sites and adds very little overhead (only a captive portal). Moreover, the remote controller benefits from the platform flexibility to increase its capacity on-demand. It is a clear improvement of existing setups which either had to have one controller per-site or to build network tunnels through the Internet reducing the end-users' quality of service.

Next section presents the detailed architecture proposal which outlines the roles of the local and remote equipments as well as the technical issues that need to be addressed in order to be implemented.

2.2 Proposed architecture

The proposal detailed in this section tries to control user connected to different sites, distant with each other and possibly owned by different cus-

tomers, from a mutualized controller hosted in a data center. These two entities interact together through the user browser to exchange authentication materials in order for the border controller to trigger a *RADIUS* access request on the remote controller. Figure 2.1 presents the big picture of these interactions, first the user device requests a web page, it is redirected onto the central captive portal where the user enters its credentials. The captive portal crafts a request sent by the user web browser to the border controller which triggers the *RADIUS* authentication. Depending on the response, the border controller opens some network access to the user device.

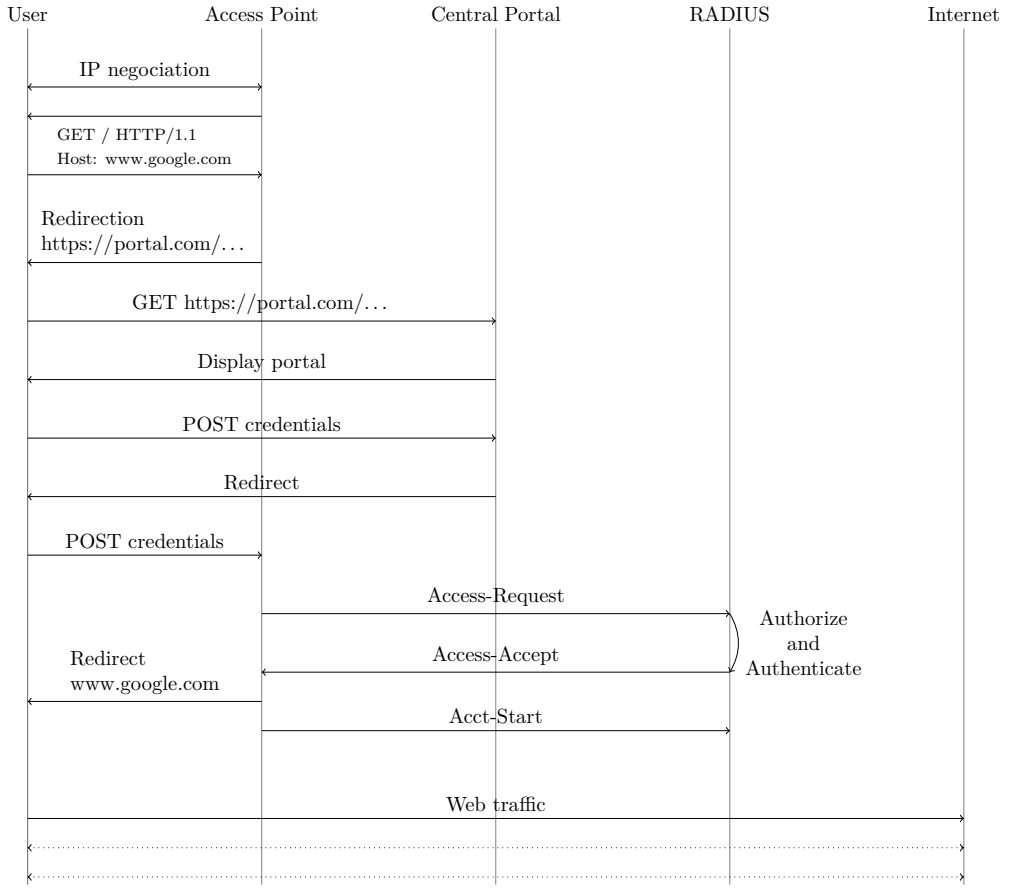


Figure 2.1 – Sequence diagram of a user device authentication

When the session ends, the border controller sends a *RADIUS* accounting stop to the central controller in order to notify and update the user session in central.

In this architecture, the user's web browser is used as a communication medium between the border controller and the central portal. This medium permits the transfer of valuable cross-layer information between

them: network information about the user device and the border controller, user credentials and feedbacks. But because data are transfered via the user device, they may be altered by him. As a result, it can not be used for critical operations such as user authentication. Here the *RADIUS* protocol provides a more secure communication channel which can not be tampered by the user.

Next section details the roles of the local equipment in this architecture.

2.2.1 Local equipment

The local border controller is in charge of controlling user access and filtering their traffic. It uses the remote controller as authentication server to decide whether a user device is authorized to access the local network or not.

The local equipment redirects web requests issued by unauthenticated users to the central web portal. This redirection is done by answering with the *HTTP* 301 or 302 code. Both codes mean that the requested page has moved, respectively permanently or temporarily. The *URL* on which the user is redirected holds a number of information including network information such as the user device's *IP* and *MAC* addresses, the *SSID* on which it is associated and informations about the *URL* it tried to reach. These pieces of information are highly valuable for the captive portal as it needs them to perform authorization checks prior to letting the user authenticate. Because the remote controller is located outside the private network, the user device's network information are hidden by the *Network Address Translation* (NAT) mechanism of the Internet gateway. Indeed private networks has been implemented behind *NATs* in order to reduce the *IPv4* address exhaustion [48] by using a unique public *IP* address for the entire network. A gateway is responsible of translating private *IP* addresses into a routable public address and vice versa. So from the public Internet, all traffic coming from a private network is seen as being emitted by the same address. This prevents the captive portal from identifying devices on the same network. For example how can it tell whether two requests were emitted by the same device or not.

The information sent in the *URL* are crucial to implement a consistent captive portal in the Cloud. Among them, *IP* and *MAC* addresses are absolutely necessary to differentiate devices whereas the other ones might be optional.

Whenever the central captive portal decides to trigger the user authentication, it orders its device to perform an *HTTP* request targeting the border controller. To handle this request, the border controller hosts a web server in order retrieve the user name and password and to execute an external script which performs the *RADIUS* request. The information transmitted include the ones presented in section 1.2.2 as well as others related with the border controller's identity. They can be used to identify the location of the user or to track its mobility over the network.

The *RADIUS Access-Accept* response holds valuable data regarding the user session. User profile, maximum session duration, quality of service are parameters which affect how the user traffic is handled. Though it is not possible to represent network services with *RADIUS* which prevents from sending the set of allowed services for the user session, one can implement this feature by sending a user profile that matches a filtering class configured on the local border controller. For instance one could setup a *guest* profile on the central database which matches a *guest* filtering class on the local border controller. The profile name is usually sent in the *Filter-Id RADIUS* attribute. Following the reception of the *Access-Accept*, the local equipment should send a *RADIUS Accounting-Start* packet in order to tell how to identify the user session to the central controller.

Then when the user session ends, the border controller is in charge of sending an *Accounting-Stop* packet containing all the session data. They include the amount of packets sent and received, the amount of data they represent, the session duration and the session ending reason. Furthermore, the user device is now considered unauthenticated again.

2.2.2 Remote controller

To control user access on the different site locations, border controllers need one or more remote controllers to provide a captive portal and an authentication server. For configuration ease and consistency, the remote controller is a place of choice to host the captive portal. It provides a unique configuration shared among all sites with potentially customized visuals depending on the user's location. The user central users database is leveraged to enable roaming between different sites while storing the session information in a unique place. Moreover, the remote controller aggregates the data from every local equipments including configuration, session logs, billing information and so on...

Regarding technical requirements, the web portal has to understand the parameters received from the redirection *URL*. Though they differ from one vendor to another, they are key to implement a decent authorization algorithm. Beside the device network information which is mandatory, a helpful information is the location on which the user is connecting from. This might be given by the *SSID* label of the Wi-Fi network, a zone label which is configured on the border controller and included in the redirection *URL* or even with a *virtual network* label supported by some vendors. The idea with this is to display a different web portal depending on the user's location. For instance one could have a web portal for the *SSID* "Book Store"which is broadcasted by a multitude of border controllers and another one for the rest of the *SSIDs* except on a particular *virtual network*.

Once the user has decided to access the network, usually by entering its credentials, the web portal has to make its browser craft an *HTTP* request targeting the border controller. This is the request which triggers the *RADIUS Access-Request* packet, hence it needs to include the user credentials as well as all the necessary information required to perform the *RADIUS* authentication. The way of building this request is detailed in section 2.3.1.

Finally, the remote controller hosts a *RADIUS* server to handle user authentications. This server is in charge of authorizing and authenticating users willing to access the network. It might implement multiple authentication schemes including plain text password 1.1.2 or password challenge 1.1.2. Moreover it has to handle session start and stop packets in order to store the information sent by the border controllers in a unique database. *Accounting-Stop* packets are really important when billing users based on their session time. It is critical to ensure that they are either correctly received by the server or that the server has a way of detecting a session which has ended with no stop packet received. In order to ensure the *Accounting-Stop* packet is received by the server, the border controller has to verify the server's *RADIUS* acknowledgment. But this is not enough in the event where the border controller is rebooted for instance. In this case, it might lose all the current sessions information so no way of sending the appropriate stop packets. To address this issue, border controllers can send accounting interim packets regularly so the server can detect whenever it no longer receives interims for a particular user session. Accounting interim must be used with care though as it increases the amount of pack-

ets exchanged between border controllers and the server and might cause major downsides regarding performance.

To provide the same user experience as the former architecture, a few technical challenges have to be solved. The next section presents them in details.

2.2.3 Technical challenges

The proposed architecture tries to externalize the captive portal by interacting with proprietary border controllers. The main challenge here is to give the same feedback to users as before. Typically this requires to inform the connecting user whether there is an error: credit time expired, wrong pass phrase, or giving him information about his current session. The feedback has to be understandable by a non-technical user which implies being translated in multiple language and not including too technical details. This kind of feedbacks is already given by the *Ucopia* solution when acting as a border controller. The challenge here is to display the same feedback when acting as a remote controller.

RADIUS Access-Reject packet may contain a *reason* attribute which gives information about the rejection. The attribute's value is most of the time a small sentence. Some border controllers will send the reason to the remote controller in such events allowing the captive portal to display it. Still the captive portal must have a translation of these errors in multiple languages. Because of this and the fact that not all border controllers send back the error message, it is not feasible to implement a correct feedback from *RADIUS* reject reasons. Instead a pre-authentication from the captive portal is proposed. Indeed because the remote controller is already able to perform authentications within the portal and to display a comprehensive feedback, it would be good to reuse these functionalities. The idea is to perform a pre-authentication when users enter their credentials, if it fails the captive portal displays the error message (translated in many languages), and if it succeeds, the user browser is redirected on the border controller to perform the *RADIUS* authentication which should succeed. The details of this implementation are described in section 2.3.2.

Another challenge arises when trying to filter users depending on their device (BYOD 1.2.1). Indeed this technology retrieves the device information including its type, manufacturer, model, the name of the web browser, the operating system... from the *User-Agent* attribute sent in every *HTTP*

requests. Though the captive portal is aware of this, the rest of the remote controller is not, and more particularly the *RADIUS* server. As a result, it is not able to perform the same kind of filtering. Section 2.3.2 details a proposition to store the user agent's information during the pre-authentication so they are available to the *RADIUS* server.

Finally the last technical issue relates to adapting with each vendor to gather the cross-layering information sent inside the redirection *URL* and to create the correct *HTTP* request to post the user's credentials. Indeed, vendors do not follow any standard to send the parameters resulting in a multitude of combinations of them to parse and understand. Apart from the naming difference and formating, vendors choose which ones they send. For instance, one vendor might send the *SSID* on which the user is associated while the others do not. As a result, integrating with new vendors is a tough task because it requires to understand its custom set of parameters, their names and their meanings. Furthermore, modifying the source code of the captive portal to add new vendors might have edge effects on the others. Regarding the *HTTP* request to post credentials on the border controller, the captive portal has to know a set of parameters: *HTTP* method (*GET* or *POST*), how to construct the border controller's host name, how to decide whether to use a secure or insecure version and what are the mandatory parameters to send inside the request. All these reasons call for the use of a model to represent each vendor, it is presented in section 2.3.1. New vendors are easily integrated inside the model without the need of source code modifications.

This section presented the proposed architecture where a remote controller, hosted inside a data center, interacts with on premise border controllers in charge of filtering user traffic. Few technical challenges were spotted regarding interactions and user feedback. The next section aims to explain the implementation details to break these challenges.

2.3 Controller side implementation

In order to provide good user experience, ease of integration with new vendors and secure filtering, some developments have to be done on the controller side. This section first presents the implementation details 2.3.1 regarding the vendor model which represents each vendor's specificity, then

the implementation of the user pre-authentication 2.3.2 with the gathering of its device information is presented.

2.3.1 Adapting to each vendor

The proposed solution to adapt to each vendor is a model representing each attribute sent inside the redirection URL as well as the *HTTP* request to authenticate and disconnect a user on the border controller. Among the long list of languages which can fulfill this task, including *JSON* and *YAML*, *XML* seems to be a good candidate because it can be parsed by lots of programming languages and platforms and is easy to write by non-programmers. This choice is somehow arbitrary as other languages would also do the job. Hence the model presented here is translatable if needed.

The list of attributes sent in the redirection *URL* is represented by a list of *XML* tags. The tag's name identifies the attribute's role, for instance the `<USER_IP>` tag describes the attribute containing the user's *IP* address. Each tag has a number of child tags to describe it. The only mandatory attribute is its key in the *URL* to extract the value. Optionally, the attribute's type can be defined as well as its default value in the event where the attribute is missing. Here is an example of the *Xirrus* vendor to represent the border controller's *IP* address on which the authentication request should be sent:

```
<HOST>
    <type>ip_address</type>
    <value>uamip</value>
    <default>185.0.0.1</default>
</HOST>
```

In the process of retrieving the attributes of a specific vendor from a *URL*, the first step is to identify the vendor. To do so, the model uses a list of attribute's keys along with the logical operator `AND` or `OR`. This list has to uniquely identify one and only one vendor because this infers the way of building the authentication *URL* which would break things if the vendor is not correctly recognized. To match the vendor, the attributes on the list has to be verified in the *URL*. For instance, looking at the *Xirrus* vendor again, its list contains only two attributes: `uamip` and `uamport`, with the `AND` operator. This means that both attributes must be present in the *URL* to identify the *Xirrus* vendor.

The last part of the model describes how to construct the authentication and de-authentication *HTTP* requests. A different tag is used to describe each one as they may widely differ. First of all, a quick reminder on how *HTTP* requests are built is required. The simpler method, *GET*, uses the *URL* to transmit parameters to the *HTTP* server. The *URL* also holds information about the server to targeted as well as the protocol to access it. Figure 2.2 presents a general *URL* split into different sections from left to right: the protocol, either *HTTP* or *HTTPS*, the server's host name or *IP* address, the *path* which is a document identifier on the server and finally the list of parameters. The other method, named *POST*, uses the request body to send its parameters list. The *URL* no longer includes them which is sometimes valuable because web browsers display it to users. When using the *POST* method, users will not directly see what information were sent to the server including their password for instance, though it does not strengthen security.

The *URL* representation defines the *HTTP* method to use (GET or POST), the protocol (HTTP or HTTPS) which depends on information sent by the border controller, how to build the server's host name, the *URI* and the list of parameters to include in the request. Regarding the host name, it is extracted from the user redirection where the border controller tells either its *IP* address or host name and *TCP* port on which it is listening on. The parameters list usually includes the user's login and password but can also embed a token sent by the border controller or a *URL* to redirect the user to after the operation is completed.

With its simplicity and its flexibility, the proposed model elegantly solves the vendor adaptation. It centralizes the specificities of every hardware in one place leaving the source code vendor independent. This is a highly valuable characteristic when increasing the number of supported equipments. Furthermore, it has little to no impact on performance as it only defines attribute names and *URL* structures, it does not increase the remote controller's workload.

$$\underbrace{http[s]}_{protocol} : // \underbrace{www.example.com}_{hostname} / \underbrace{path/document.ext}_{Path} \underbrace{?key1 = value1 \& key2 = value2}_{parameters}$$

Figure 2.2 – Representation of the *URL* in a *GET* request

2.3.2 Improving user experience and data gathering

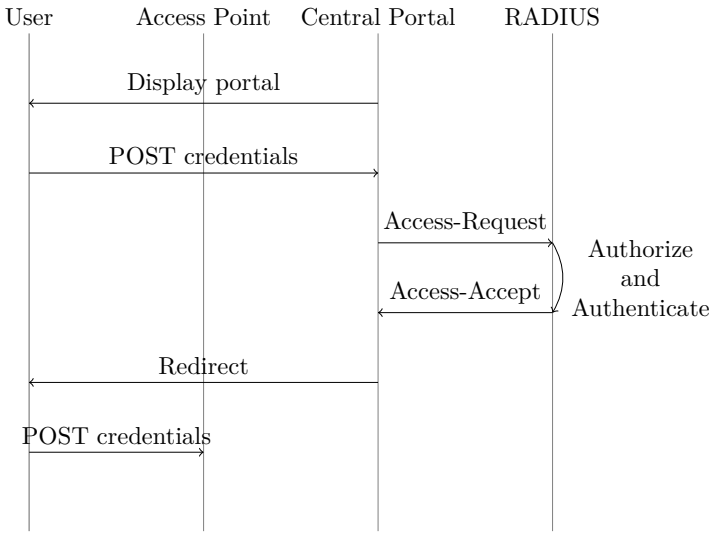
Currently, the implementation allows end-users to get a remote captive portal, authenticate against their local border controller and disconnect from it. This minimal set of features is enough to control users in a private network. Though functional, it is not user friendly enough. Indeed in the event where the authentication request is rejected, it is difficult to provide the right feedback to the user about the triggered error. Because the border controller performs the authentication request using the *RADIUS* protocol, only a *yes/no* answer, including an optional reason message is sent back by the server. This reason message is by no mean self explanatory for everybody: foreign language, technical information or error codes. That is why the captive portal should be the one to display a comprehensive feedback understandable by a multitude of people. Section 2.2.3 also outlined that border controllers do not always send the *RADIUS* reason message when authentication fails leaving the captive portal powerless to display anything but a generic error.

Implementing a user pre-authentication prior to building the *HTTP* request to post user's credentials on the border controller addresses this limitation. Indeed the captive portal is able to trigger an authentication without starting a new session and able to retrieve the resulting error code. Depending on it, the portal can send the proper feedback to the user and prevent the border controller from triggering an authentication request which will fail. Figure 2.3 is an updated version of the interactions between the border and the remote controllers. The pre-authentication is done right after the user sends its credentials to the captive portal.

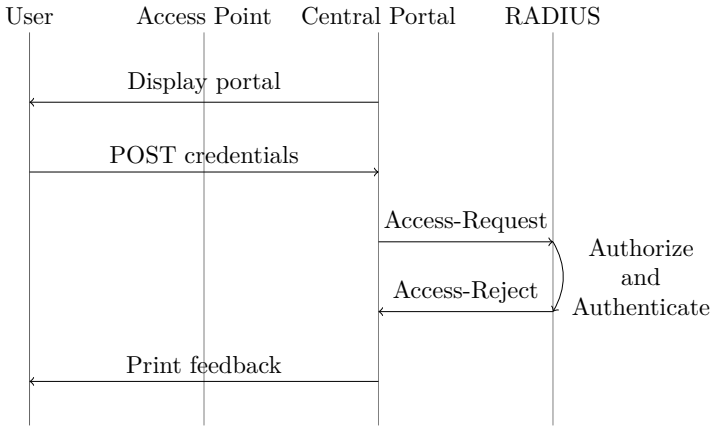
Moreover, the pre-authentication is a great opportunity to implement the *BYOD* filtering. As only the captive portal is able to retrieve these information from the *User-Agent* attribute, it is the only place where they can be checked and stored if needed. The enhanced implementation uses the captive portal in order to fulfill to *BYOD* filtering as well as storing these information into the session database so they are available for reporting and statistics.

2.4 Summary

This chapter presented an innovative architecture in which a network access controller is mutualized between multiple distant networks or sites.



(a) Successful



(b) Failed

Figure 2.3 – Pre-authentication sequences

This architecture addresses a key market segment where clients can't afford to install a network controller per site. In addition, this architecture has a number of advantages compared to former ones. It first benefits from data center hosting to provide platform flexibility. This gives the ability to absorb peak of connections for instance. Furthermore the controller's costs are split between every clients. This makes the solution more profitable for the company and less expensive for each client. Also they are no longer forced to buy the hardware as they can rent the controller for the time period they want.

Having the network controller outside the private network brought a set of challenges related to cross-layer information sharing. Indeed in this first implementation, the network controller is unable to access such data by it-

self. Routing over the Internet, Network Address Translation performed by network gateways are example of mechanisms which hide cross-layer information in packets transmitted over the public network. As a result, on-site session border controllers need to share the information available at their level with the remote controller. First when unauthenticated users access a web site, the border controller redirects the request to the captive portal. The target URL is populated with parameters holding the cross-layer data so the web portal get retrieve them. Then when the user authenticates, cross-layer information are sent within the RADIUS request.

The first challenge for the remote network controller is to be able to interact with a wide range of border controllers. Indeed, because their is no standard way of transmitting cross-layer information inside an HTTP URL, each vendor has implemented it's own set of parameters. Moreover the interactions with the border controller are also vendor dependent and changes with new releases.

A model was designed to represent each vendor. This model allows the captive portal to recognize a vendor's signature based on the set of parameters present in the redirection URL. After recognizing the vendor, all the cross-layer information can be retrieved based on the key names of each parameters. Finally, the model describes how to generate the right HTTP request to the border controller in order to trigger an authentication and a de-authentication requests. This model allows to add new vendors without modifying the source code of the Ucopia product. This is a clear improvement for the company as non-developers can add new products to the list of supported hardware.

The second challenge we faced during this implementation was to provide the same user experience as the usual Ucopia product does. Typically, users must have a comprehensive feedback when they connect to understand why an authentication failed, how long their session is going to last and what network services they are allowed to use. Because the real authentication is performed by the session border controller using RADIUS, the only feedback displayable to the user is the RADIUS' response. This response, usually in English is too technical for end-users to fully understand what happened. Additionally, the lack of multilingual feedback is unacceptable by most Ucopia's clients.

To resolve these issues, we implemented a pre-authentication within the web portal. The idea is to trigger an authentication and retrieve

the feedback sent by the Ucopia authentication server. This feedback is already translated in many languages and not too technical. This pre-authentication is also the opportunity to share valuable information held inside the client's HTTP request. For example, the User-Agent field contains lots of information about the user device including Operating System, browser type and version etc... These information allow to differentiate the network controller based on the user device's type (BYOD). The implementation of this pre-authentication phase extensively used cross-layer information in order to identify a user device between the captive portal and the RADIUS server. Indeed, in order to retrieve information on both sides, common knowledge must be shared (e.g. the device MAC address).

Finally it is worth mentioning that this remote network controller has already been deployed in various Ucopia projects including stadiums and train stations. The code was released in the 5.0 Ucopia version in 2014 and entirely developed by the author of this thesis.

This implementation is based on specialized hardware implementing custom HTTP requests to share cross-layer information with a remote captive portal and trigger user authentications. Because these hardware can not be controlled by the remote controller directly, new features are hard to develop. Moreover the configuration of such architecture is harden by the fact that every border controller needs to have all the user profile information in terms of network services for example. The next chapter presents a different approach to implement this architecture using *SDN* equipments instead. It aims at addressing the limitations of the current implementation regarding the interactions between the controllers, both for the user authentication and network filtering.

Chapter 3

An SDN approach

Software-Defined Networking (SDN) [57] [52] [37] is a recent networking paradigm that decouples the data plan from the control plan [34]. *SDN* architectures aim to be manageable and dynamic by enabling a programmable control plan and a hardware abstraction. Network equipments communicate via *SDN* protocols with other computers which dictate how the network traffic has to be forwarded. Today, only a fraction of network equipments in the market is *SDN* capable but this is changing rapidly especially regarding Wi-Fi access points where a number of vendors integrates some *SDN* capabilities [53] [9]. Looking at the growth of Wi-Fi access points and their transformation into *SDN* equipments, it is fair to assume that in few years, most Wi-Fi hotspots will be *SDN* enabled.

In that regard, if border controllers become *SDN* equipments, one could control how they forward packets from a remote location which is somehow what was done in the previous architecture. Here though, hardware is abstracted and communications between the equipment and a controller are made using a standard protocol. Implementing a border controller only with *SDN* equipments would address the problems raised in the last chapter: vendor agnostic and runtime control of the forwarding plan. Moreover, assuming the majority of network equipments will be *SDN* capable in the next few years, any kind of hardware would be able to act as a border controller which is a clear improvement compared to the current architecture where specialized hardware are required.

This chapter is also the opportunity to present a concrete implementation of the cross-layering framework using SDN equipments. It presents a novel mechanism to modify HTTP payloads in order to include cross-layer information. The implementation focuses on HTTP but can be extended

to support any kind of network protocols. Additionally, it is transparent for equipments on the network as it only involves SDN equipments and their controller.

This chapter is arranged as follow: first section 3.1 discusses the pros and cons of this approach and put it in perspective with novel technologies like *Network Function Virtualization* (NFV) [8] [42]. Then section 3.2 presents the *OpenFlow* protocol both for its technical aspects and its limitations. Section 3.3 and 3.5 explain how these limitations can be overcome in order to implement a captive portal redirection.

3.1 Discussion

Piloting network equipments is not something new, vendors often use their own protocols to remotely configure and manage them from a network controller. It is especially true with Wi-Fi equipments. Of course, the controller is part of the vendor's package when he sells the equipments and is only compatible with them. With this technique, vendors force customers to use the equipments of a single brand for their entire architecture. Other non-proprietary protocols have emerged outside the Wi-Fi world such as *NETCONF* [60] [45]. This protocol developed by the *IETF* aims to provide a standard way of pushing and retrieving configurations from network equipments regardless of their brand. The raising of *SDN* capable hardware in Wi-Fi access points opens up new opportunities to build heterogeneous architectures controlled from a single controller.

Despite the keen interest developed around *SDN*, building a border controller with generic hardware is hard. Indeed, everything has to be implemented in software, from the captive portal redirection to the firewalling rules. Furthermore, *SDN* protocols were not built around the idea of controlling user access but rather about the way of forwarding packets inside an equipment. This limits protocols features to only networking purposes.

Network Function Virtualization is another novel technology rapidly growing in the networking community. The idea is to instantiate on demand any kind of *Virtual Network Function* (VNF) on top of an hypervisor. It leverages all the benefits brought by virtualization to migrate functions from one place to another inside the network, provide high availability and flexibility. A *VNF* is the implementation of a network function, for instance it could be embodied as a firewall, a switch, a router or even a session border

controller. Though to instantiate a *VNF*, one has to have control over an hypervisor inside the network. This hypervisor is part of the *Network Function Virtualization Infrastructure* which gathered all pieces of the network along with the access methods to equipments. Such infrastructure is hard to deploy and maintain, it requires hardware, data centers and expertise. That is why *NFV* is suited for carrier-grade service providers: they already have buildings, expertise and hardware, furthermore they have control over the entire network.

In the context of private networks, it is unlikely to find hypervisors inside a customer's network. Even then, there is little chances that a third party can instantiate its own *VNF* on top of it. It requires a strong integration in terms of orchestration process, trust and maintenance. A solution can emerge in the near future using set-top boxes provided by Internet provides in order to host a "session border controller" *VNF*. These hardware are completely controlled by the service provider and can easily be integrated as part of its *NFVI*. This solution might require to update some hardware to include virtualization support as well as an hypervisor.

Service providers are only interested in providing a service to their customers. For instance they provide Wi-Fi hotspots via Internet boxes only accessible for their clients. Furthermore, the owner of the Internet access has no control what so ever on the hotspot provided by its box. This is not the kind of solutions presented in this thesis, the client should be able to customize and control it's network. As long as *NFV* remains a carrier-grade provider technology, it seems difficult to build a independent customizable network access solution *VNF*. This is not irremediable in the future but for now, *SDN*-based solution seems better suited for the purpose of implementing a private network access controller.

Next section presents the *OpenFlow* protocol which defines a set of interfaces for network equipments to delegate their forwarding decisions to a remote controller.

3.2 OpenFlow

OpenFlow [54], *LISP* [24] [30] or *OpenDaylight* [31] are examples of SDN protocol implementations, that can help simplify and improve network guest access configuration and management. *OpenFlow* is open source, popular and mature, all of which makes it an ideal candidate to support

the following proposed architecture.

3.2.1 Protocol overview

Although it was originally designed for network experimentation, *OpenFlow* is now implemented by various hardware vendors including HP, Juniper and IBM [62]. *OpenFlow* does not rely on any proprietary feature. It abstracts the underlying hardware design and aims to be adopted by a large number of equipment vendors. At its simplest level, the protocol lets an *OpenFlow switch* be configured by an *OpenFlow controller*. The *OpenFlow switch* requests and receives traffic rules from the *controller* over a trusted *Transport Layer Security* (TLS) tunnel. *TLS* implements both an end-to-end encryption of data payloads but also a mutual authentication between the switch and the controller using signed certificates. A set of default rules is configured by the remote controller on the switch, which processes and enforces these rules in its packet forwarding table.

Internally, the OpenFlow switch uses a flow table and a standardized interface to add and remove flow entries. A *flow* is a set of packets which share the same properties. A flow entry consists of a matching rule and a set of actions. *OpenFlow* specification requires the switch to act on protocols of layer 2 to 4 of the OSI model [35] including *Ethernet*, *VLAN 802.1q*, *MPLS*, *IP*, *TCP* and *UDP*.

OpenFlow rules are grouped into chained rule tables. Each packet is processed against the matching rules of the current table. If no rule is matched, the packet is passed to the following rule table. If the packet matches a rule, the processing can either jump to another rule table or a specific set of actions can be executed. As an example, actions associated with the rule and a matched packet could be to:

— drop the packets from the flow,
— send the packets on a particular port of the equipment,
— apply bandwidth limitation to the flow,
— modify header's fields including *IP* addresses, *VLAN* tag, ...

Whenever a packet can not be matched by any existing rules, the switch triggers a *table miss* action sending the raw, or part of the packet to its controller. After analysis, the controller tells the switch what to do with this packet by inserting a new entry in the flow table. Control information is also associated with each rule. For example, the controller may indicate when a rule expires, which is an efficient way to grant network access to a device

for a limited period of time. *OpenFlow* switches also provide accounting information for each flow allowing the controller to retrieve valuable data at any time.

OpenFlow leverages the usage of *TCP* in order to have bi-directional communication between switches and the controller. Because the switches initiate the *TCP* session, it traverses *NAT*s and firewalls in between. This property allows a controller to modify a switch's forwarding table whenever needed. It addresses the lack of interactions of the previous architecture.

3.2.2 Packet matching

Each *OpenFlow* switch has a number of flow tables. They contain rules to match and take action on incoming packets. Whenever a rule matches, its actions are pushed into the packet's action set. If at one point the packet has to be sent on an outgoing port, these actions will be applied. A rule might also affect the internal processing of a packet by jumping to another table rule, dropping the packet or sending it. A switch can send a packet on one or many physical ports as well as a number of *virtual* ports which have special meanings. For instance there is a virtual port for the communication link with the controller, to send raw packets, or another one to *flood* all the ports of the switch.

Figure 3.1 shows how an incoming packet is matched through the different table of the switch. It starts with an empty action set and as rules are matched, it gets filled up with actions. In the end, when the packet is about to be sent, all the actions of the set are applied and the packet is sent onto an outgoing port.

Matching rules are composed by a number of header fields-expression tuples. The switch applies the expression on the packet's header field's value. If every expressions match, it triggers a rule match. A wide range of headers can be used in *OpenFlow* rules including almost everything in common protocols from layer 2 to layer 4: *Ethernet*, *IP*, *TCP*, *ICMP*, ... Regarding actions, switches have to be able to modify a subset of the packet's header fields including addresses, port numbers, pushing/pooping a *VLAN* or *MPLS* tag. These packet's modifications might break the checksum of protocols like *IP* or *TCP*, hence the switch must re-compute them.

Finally, the controller exposes public API in order to create/modify and retrieve information from flows. They are often referred as Northbound

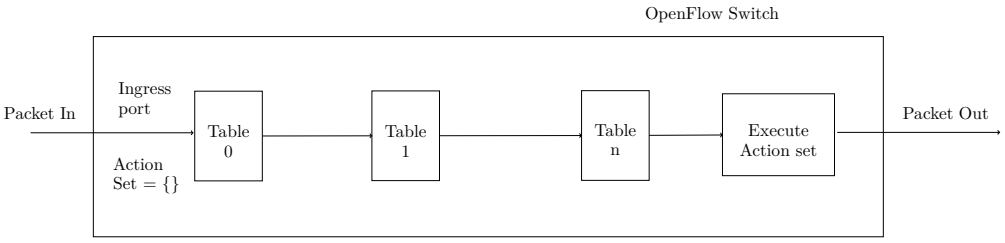


Figure 3.1 – Table matching of an incoming packet inside an OpenFlow switch [35]

API. Given a controller, an external application (e.g. a network controller) can learn the network topology and create flows on specific switches.

3.2.3 Limitations

OpenFlow is a very powerful protocol which enables real network instrumentalization regardless of the hardware. In order to be easily integrated, the specification does not require the hardware to implement advanced networking features. Indeed only protocols' headers are matched and modified.

On the other hand, current equipments are able today to perform advanced networking treatments such as service classification using *DPI* techniques. Fine-grained filtering on web services as well as advanced reporting can be achieved. Moreover, session border controller are often in charge of intercepting user flows in order to force the usage of an applicative proxy or perform *HTTP* redirection for unauthenticated users. *OpenFlow* is limited compared to such hardware because it is unable to instrumentalize upper layer protocols.

This is problematic in the present context. Not only the captive portal must be able to differentiate user devices belonging to the same private networks like in chapter 2, but also now, it needs to notify the *OpenFlow* controller about newly authenticated users. Indeed the controller takes decision based on packets network information only. To build a network access solution, the system must be able to bind an identity to a device as presented in chapter 1. Lacking common device identifier prevents the captive portal from pushing access rules to the controller.

The *HTTP* redirection presented in chapter 2 would solve that issue. It provides enough information to the captive portal to identify devices belonging the same private network. Despite *OpenFlow* being unable to perform such redirection, it gives the ability to implement custom processing

inside the controller. This is the main challenge of this thesis, implement the captive portal redirection containing cross-layer network information only using *OpenFlow* equipments. The implementation focuses on the captive portal redirection but can be extended to any kind of use cases. Next section presents how *OpenFlow* limitations can be overcome in order to properly implement the redirection of users.

3.3 Proposal to overcome OpenFlow limitations

Last section outlined the need for border controllers to implement a captive portal redirection including the user device's network information so they are available to the captive portal. This step is absolutely crucial to provide enough information to allow the notification of the *OpenFlow* control so it can open network access to newly connected users.

Despite *OpenFlow* equipments being capable to redirect traffic to other hosts, for instance by modifying the destination *IP* address of a flow, packets sent on the Internet see their source IP address being masked. Figure 3.2 describes this mechanism, packets sent by a network device have their destination address re-written by the *OpenFlow* equipment and forwarded to the Internet gateway. The gateway then sends the packet with its public *IP* address so the server can reply to a routable address. Leveraging this technique, one can intercept the user web traffic and redirect it to its web server implementing a web portal redirection. But again, the web server lacks network information about the user device.

To provide enough information to the web portal, unauthenticated user devices are redirected using *HTTP*. This redirection includes all necessary data to identify the device uniquely and retrieve its location. In the current architecture, both the *OpenFlow* equipment and the controller have access to topology information. That is because the switch is directly in the path of packets and it sends raw packets to its controller to let it decide how to forward them. This capability is leveraged to tunnel network flows from the switch to its controller. This way the controller can intercept any kind of traffic from a switch. The technical details of this proposal are explained in section 3.4.2. The implementation aims at intercepting HTTP traffic sent by unauthorized devices, tunnel them to the controller and reply with a custom HTTP redirection.

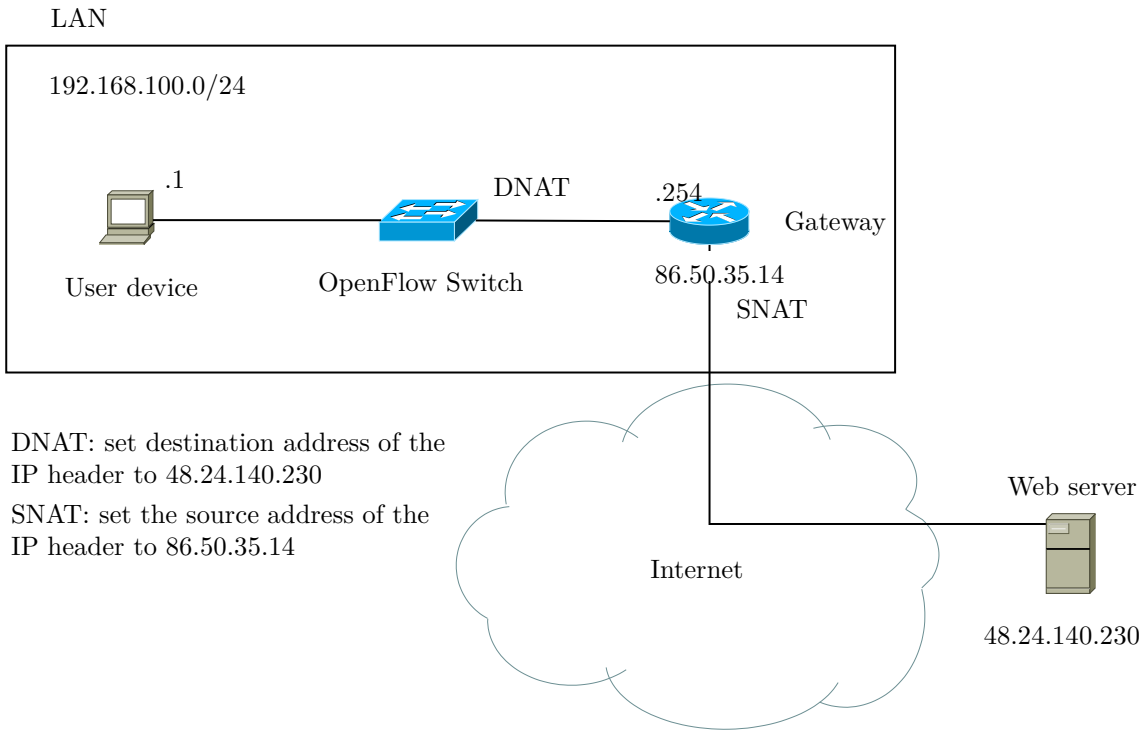


Figure 3.2 – Flow redirection using an OpenFlow switch

On paper, this solution is not too hard to implement because *HTTP* is a simple protocol. But in practice, in order to send applicative data, all the underlying protocols have to be implemented in the first place. Regarding *HTTP*, a *TCP* connection is required between the client and the server before they can communicate. Similarly, to setup a *TCP* connection between two distant peers, they need to have an *IP* connectivity and to have an *IP* connectivity, they need a layer 2 access (e.g. *Ethernet*).

So, to send a redirection to a user, the *OpenFlow* controller must correctly handle all network protocols. It is important to emphasis that the *OpenFlow* controller is a userland process executed on a regular operating system. It receives data from switches through regular *sockets*. *Socket* objects abstract the complexity of exchanging data through a network: data loss, peer identification, ... Generally speaking, user processes do not handle network protocols themselves. They leverage their operating system's network stack to send and receive applicative data on top of a transport layer. The network stack is in charge of sending the data payloads to the right recipient, implementing the correct set of protocols. When a user packet is sent to the controller, it is transmitted raw, including the lowest protocol layers. If the controller wants to reply to a user device, it needs

to implement all layers correctly.

Because network protocols are very hard to implement properly, trying to implement even a small portion inside a userland process constitutes a huge amount of work. Instead the *OpenFlow* controller can act as a network tunnel termination receiving raw packets from *OpenFlow* messages and forwarding them directly onto a network interface. Furthermore, it has to redirect the traffic onto a specific host which implements a web server. This way HTTP can be correctly implemented. The web server is configured to reply with an *HTTP* redirection to any request it receives. Finally the controller identifies the redirection and modifies the target *URL* in order to append the device network information.

Next section presents the implementation details of the network tunnel over *OpenFlow* proposal. Then section 3.5 presents how flows are modified by the controller to implement the captive portal redirection.

3.4 OpenFlow network tunnel

Network tunneling is a widely spread technique to encapsulate a protocol in another one. For instance in order to transition from *IPv4* to *IPv6* networks, *6to4* tunnels encapsulate an *IPv6* header inside an *IPv4* one so the *IPv6* payload can be routed inside an *IPv4* network. Another example of network tunnels is *Virtual Private Networks* (VPN) in which *IP* payloads are encapsulated inside a protocol able to cross other networks. Service providers can provide *VPN*s over *IP* whereas individuals usually use *VPN*s over *TCP* or *UDP*.

The current proposal uses an OpenFlow switch to intercept network flows and encapsulate them inside OpenFlow `packet-in` messages. The switch sends them through the encrypted channel to its controller. Upon reception, the controller decapsulates the packets from the OpenFlow messages. These packets can not be sent directly onto a local interface because their destination MAC and IP addresses are populated by the user device. The information they hold are only relevant from the device point of view so the controller has to modify them accordingly. Namely the destination MAC and IP addresses must be replaced by the ones of the targeted server.

Because *OpenFlow* is implemented over *TCP*, or *SCTP*, the structure of packets sent by the switch to its controller looks like this:

$$Ethernet \leftarrow IP \leftarrow TCP \leftarrow OpenFlow \leftarrow Ethernet \leftarrow IP \leftarrow TCP$$

Only the green part is received by the *OpenFlow* controller. It is then important to understand the protocols with which the controller has to work with in order to translate addresses. Regarding *Ethernet* and *IP*, they are pretty simple and well documented in various papers [27] [64] [20]. *TCP* is also well documented [28] [26] but has some technicalities which require further details for a good understanding.

3.4.1 TCP analysis

TCP is a client-server, reliable, connection oriented protocol. It allows a client and a server to reliably exchange data without experiencing packet loss nor unordered packets. In order to provide these functionalities, *TCP* extensively uses sequence numbers to identify segments of data as they are transmitted over the wire. Each side generates a random sequence number during the initial three-way handshake:

— The client sends a `SYN` message to the server with its sequence number A.

— The server replies with a `SYN/ACK`. The packet's sequence number B is chosen randomly by the server. Additionally, the server acknowledges the client's `SYN` by populating the `ACK` number with the client's sequence number A plus one.

— Finally the client acknowledges the server's `SYN/ACK` with an `ACK` message containing the server's sequence number B incremented by one as well.

Figure 3.3 presents the *TCP* handshake sequence. It shows how both sequence numbers are sent to the other peer then acknowledged. At this point, the client and the server have established a full-duplex communication link where each side is able to send data to the other whenever it wants.

The connection termination uses a four-way handshake in order for both sides to acknowledge it but this is out of the scope of this thesis.

Every *TCP* packet has a number of required fields: a source and a destination port number to identify applications and a sequence number. The sequence number refers to the position of the current packet inside the list of packets sent by the peer. It is equal to the initial sequence number A plus the total amount of data sent since the initial handshake:

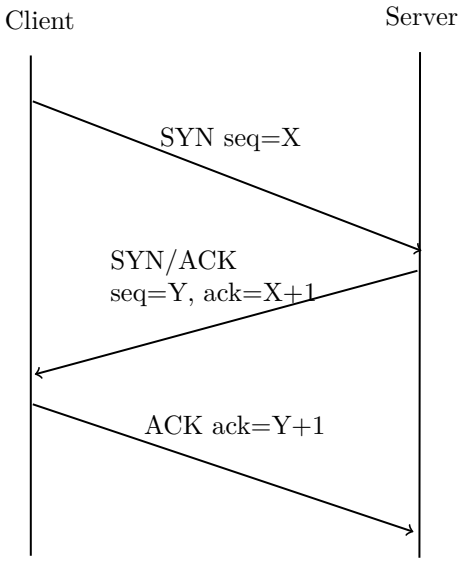


Figure 3.3 – TCP handshake

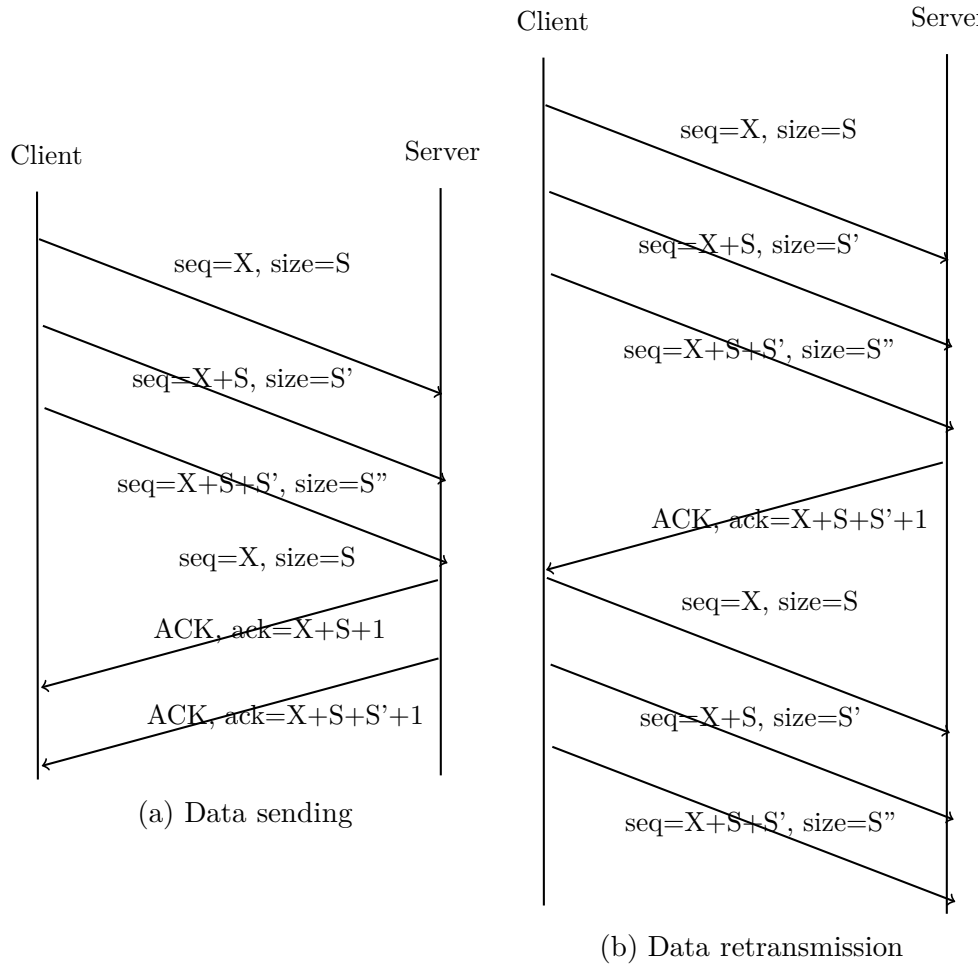
$$Seq_n = A + \sum_{i=0}^{n} len(P_i) \tag{3.1}$$

It is important to emphasize that this is unsigned integer arithmetics so every operation is done modulo 2^{32} because of sequence and acknowledgment numbers being represented on 32 bits long integers.

Every segment of data has to be acknowledged by the other side in order to ensure it was correctly received. The acknowledgment is sent using the `ACK` flag in addition to an acknowledgment number equal to the last data sequence plus the size of the data segment plus one:

$$Ack_n = Seq_n + len(P_n) + 1 \tag{3.2}$$

A retransmission timeout is triggered whenever a segment is not acknowledged fast enough. In such cases, the sender resends all the data from the unacknowledged segment. Indeed, when a peer sends data to the other, it does not have to wait for every segments to be acknowledged before sending the next one. This parallelization increases the overall throughput by having multiple packets on the wire at the same time. Figure 3.4a shows how packets are sent in parallel and acknowledged little-by-little. Figure 3.4b shows a *TCP* retransmission of a lost packet, it outlines the retransmission of every subsequent packets from the one which was lost. Packet retransmissions are bad for the overall throughput and impact the jitter.



(a) Data sending

(b) Data retransmission

Figure 3.4 – Data transmission over TCP

Additionally, sequence numbers allow the receiver to re-organize the packets in the right order and remove duplicates, before sending the data payloads to the application.

Finally, *TCP* computes a checksum of every packets in order ensure their integrity. The checksum creation takes into account part of the *IP* header fields such as addresses plus the *TCP* header and payload. Failing to verify a packet's checksum will eventually result in a packet retransmission because it will not be acknowledged.

This small introduction to *TCP* will help the reader in subsequent sections to understand how payload modifications break the sequence/acknowledgment mechanism and what needs to be done to keep a correct state between the client and the server.

Next section presents how packets are handled by the controller in order to implement a network tunnel through *OpenFlow*.

3.4.2 Packets handling

To properly implement a network tunnel through *OpenFlow*, it is important to understand how packets have to be treated by the controller. Indeed, despite packet encapsulation being a built-in *OpenFlow* feature, it is only intended to help the controller identify network flows [35] [56].

In the current proposal, the *OpenFlow* switch is in charge both of intercepting user flows, configured by the controller, and sending them to its controller via the `packet-in` *OpenFlow* message. When a `packet-in` is received by the *OpenFlow* controller, it contains a raw packet in its payload. Because the payload already holds a valid packet, sent by a user device, it can be directly sent on a network via a concrete interface.

Operating Systems provide several ways to send and receive raw packets onto a concrete interface. They bypass the network stack in order to sniff packets (*libpcap* [70]), forward traffic from user land process or even implement low level protocols like *DHCP* or *avahi*. *Berkeley Packet Filter* [63], raw socket [23] or *netmap* [51] are example of OS implementations to bypass the network stack.

During the implementation, the *BPF* subsystem was used. It provides an effective packet filtering language as well as decent performance for reading packets. For packet emission though, *BPF* lacks memory cache which impacts the achievable throughput. Despite this, the results shown in section 3.4.3 are good enough for a first implementation. In future work, *netmap* should be tested in order to see if it enhance the overall throughput of the solution. Indeed this project aims at saturate 10 Gigabytes links from a software application.

Raw packets sent by user devices are only valid with their Local Area Network. Indeed, the address fields are only relevant within this scope: for instance the destination MAC address permits to forward the packet to the right host locally which then routes the packet to the right public server. Inserting packets emitted from on LAN to another host simply does not work, address spaces must match, *ARP* resolution must be implemented to learn hosts from their IP address and so on. In order to build a working tunnel between two LANs, a L2 link must exist between them (no routing) or routers must be configured to route traffic from one to the other. Because traffic is already forwarded with the level 2 layer, it is easier to use the former method: configure the remote subnet, hosting the web server with the same address space as the client's LAN. Later sections will introduce a

concept of address translation in order to implement the solution regardless of the client's LAN configuration but for the sake of simplicity, this section starts with a simple scenario.

So packets received by the controller are sent unaltered to a network interface, either physical of virtual, using the *BPF* subsystem. On the returning side, packet are sniffed to retrieve raw responses from the server. These packets are sent to the correct switch using the *OpenFlow* `packet-out` message on the right physical port. Like the `packet-in` message, `packet-out` holds a raw packet in its payload and makes the switch sending it to one or more ports.

Benefiting from this, user traffic is tunneled from its local area network to the *OpenFlow* controller's network. With proper network configuration, devices inside the LAN are able to communicate with remote machines. Figure 3.5 presents a simple representation of such setup. Packets are tunneled through the *OpenFlow* protocol from the switch to the controller which forwards the raw packet to its network interface. Given proper configuration, the packets are transmitted to another machine within the remote LAN and handled correctly by its network stack.

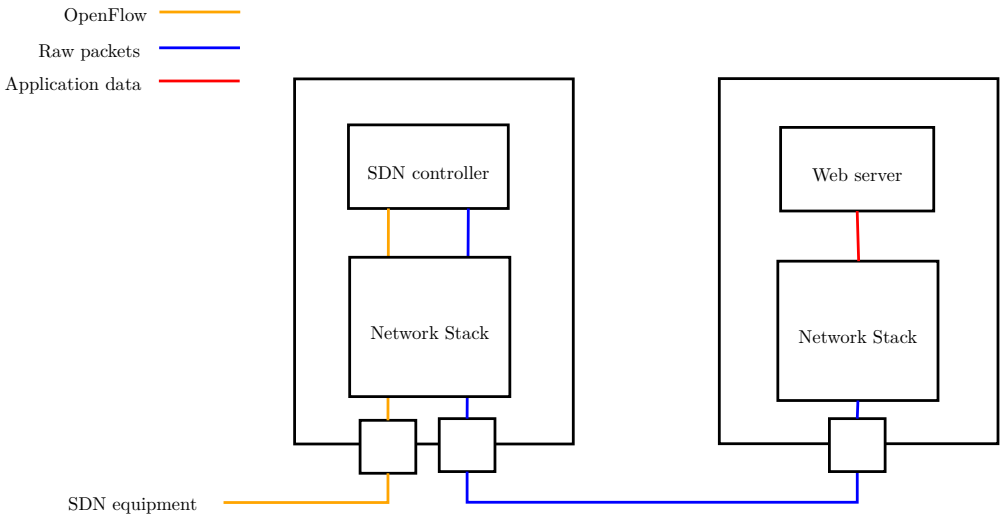


Figure 3.5 – Network tunnel through the *OpenFlow* protocol

Because packet encapsulation reduces the effective payload of each packet, the Maximum Transmission Unit needs to be reduced. Indeed, physical links have a capacity limits which force packets not to exceed a certain size. Whenever a packet exceeds that limit, it is split by the Operating System so each segment can be sent accordingly. Because the user device is not aware of the network tunnel and that the *OpenFlow* controller has

no means to configure its *MTU*, the TCP's Maximum Segment Size is set by the server. That TCP's option allows both peers to advertise the maximum size of the TCP payloads to transmit in order to reduce the packets' fragmentation [65]. Additionally because a user process slows down the forwarding of packets [50], it is important to ensure enough bandwidth is delivered by the present tunnel. Indeed it is intended to scale in production to up to thousands of concurrent users for a single controller. A bandwidth test was setup to study the implementation. The main objective is to reach the controller's limit as it is the bottleneck of the architecture.

3.4.3 Performance measurements

Tunneling traffic always decreases bandwidth because it reduces the effective data payload. By encapsulating traffic inside an applicative protocol like *OpenFlow* which is already wrapped inside an encryption layer, the amount of user data carried in packets is highly reduced. Moreover every user packets is forwarded by the *OpenFlow* controller, a user process, which is slow.

The test involves ten machines with different hardware, from lightweight equipments to heavy bare metal servers. Table 3.1 summarizes the hardware capabilities along with the number of servers of each type. Each one of them runs an OpenVSwitch [16] instance (v2.3.1) controlled by an OpenDaylight [31] controller. The controller implements our proposal, it uses the *BPF* subsystem to bypass its network stack. As a side note, the controller runs FreeBSD version 10.1 and the other equipments run GNU/Linux with Debian 7. Additionally, the experiment needs to be isolated from the concrete local network. On the controller side, the applicative server is hosted as a virtual machine on the FreeBSD system using its hypervisor: *bhyve*. On the other hand, the *mininet* [69] project allowed to create virtual networks inside each machine. Mininet leverages the Linux kernel namespace to create interconnection between virtual interfaces in order to simulate a real network. Each mininet network is controllable by an OpenFlow controller thanks to the OpenVSwitch instance.

To generate traffic and saturate the tunnel link, the *iperf* [11] program was used. It is a lightweight yet powerful and flexible program which generates TCP or UDP traffic between a client and a server. To ensure the tunnel link is saturated, each CPU of each machine executes an *iperf* instance. The TCP Maximum Segment Size [43] [47] is set to 1400 to prevent

#	Name	CPU	RAM
1	lunar	Xeon E3-1270, 3.5 GHz, 8 cores	16Gb
1	venus	Xeon X3450, 2.67 GHz, 4 cores	2Gb
1	titan	Intel Atom D525, 1.8 GHz, 4 cores	2Gb
1	neptune	Pentium Dual E2220, 2.4 GHz, 2 cores	1Gb
2	saturn	Xeon E5-2660, 2.20 GHz, 32 cores	32Gb
4	solar	Xeon E5645 2.40 GHz, 24 cores	23Gb
1	OpenFlow controller	Intel i5-3550, 3.3 GHz, 4 cores	8Gb

Table 3.1 – Hardware specification of the lab equipments

fragmentation of packets. The value was chosen arbitrarily and might not correspond to the optimal MSS value. Despite not being optimal, results are good enough to plan a production release and future works will aim at optimizing such metrics in order to increase the global throughput.

Figure 3.6 presents the results of a first experimentation involving the four least powerful hardware. The global throughput seen from the virtual machine point of view is plotted. It outlines a clear upper bound of 68Mbits per seconds with a peak up to 68.2Mits/s. Despite not being enough to saturate a link within a LAN, this is more than enough to saturate multiple ADSL links at the same time. To confirm the limit comes from the controller, the 6 reminding machines were added. Results are plotted in figure 3.7. It demonstrates that the same upper bound of 68Mbits/s is reached. This confirms it is the controller's limit.

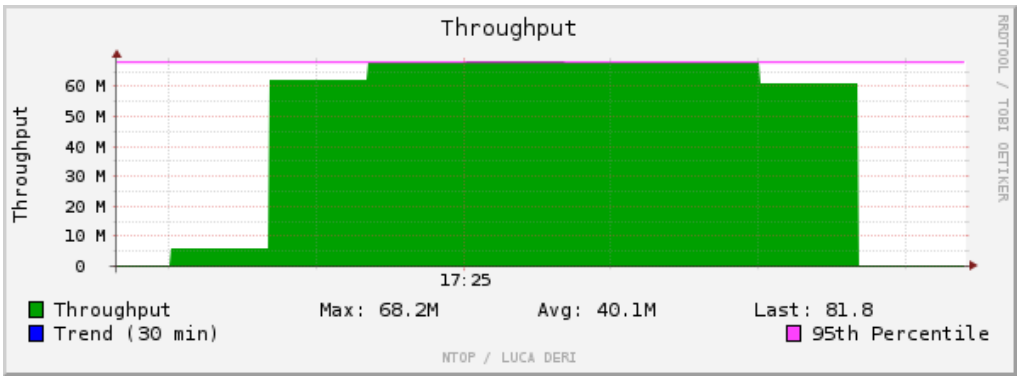


Figure 3.6 – Global throughput at the server's network interface with 4 switches

Of course this limit is not set in stones as it depends on the hardware characteristics of the controller. Though the limit might fluctuate around 70Mbits/s, it is unlikely that improving the hardware changes drastically these results. On the other hand, testing other network stack bypass mech-

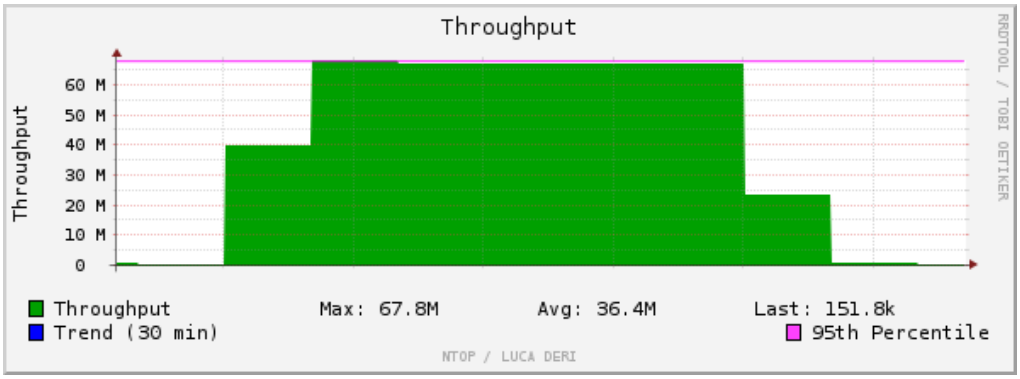


Figure 3.7 – Global throughput at the server's network interface with 10 switches

anism might improve these results especially with the new *netmap* subsystem.

For the purpose of redirecting unauthenticated users, this limit is totally acceptable as it is bigger than most non-optical fiber Internet access bandwidth. Moreover, this limit is also enough for most applications which does not require high bandwidth. This first milestone is important to show the feasibility of the solution. With these results in hand, next section presents the implementation details of the captive portal redirection.

3.5 Captive portal implementation

Implementing a captive portal redirection for users located inside a controlled network is not easy. Indeed, the redirection has to work for any kind of devices, configurations and network structures plus user should not configure a thing. The proposed solution is to use *OpenFlow* tunnels to intercept user flows, modify their destination so they are sent onto a controlled web server and finally append useful information inside the *HTTP* response. These last two steps are detailed in the next sections.

3.5.1 Traffic redirection

Since the *OpenFlow* tunnels technique presented in last section requires a special setup both on the user device and the controller's network, it can not be deployed in production as is. Indeed, the context in which border controllers are deployed is out of the control of the controller and the captive portal. No assumption can be made about the environment except that devices have an *IP* address and a default gateway configured

(along with a working ARP resolution). In this situation, to implement a captive portal redirection, the proposed solution has to work with any kind of network configuration. Because it is not possible to adapt the remote controller's network to every networks, it is proposed to implement a *Network Address Translation* by modifying user flows' addresses.

When a device connects to a remote server (outside its *LAN*), it sends a packet to its gateway with the following information:

	Source	Destination
Ethernet	MAC_{device}	$MAC_{gateway}$
IP	IP_{device}	IP_{server}

In order for the web server's network stack to accept packets, the destination *MAC* and *IP* address must be his.

Addresses are modified by the controller in the following manner:

— The destination *IP* and *MAC* addresses of packets emitted by users are replaced by the $IP_{webserver}$ $MAC_{webserver}$.
— The destination *IP* and *MAC* addresses of packets returning to users are replaced by IP_{device} MAC_{device}.
— The source *IP* address of returning packets is replaced by IP_{server} which is the initial destination *IP* address so the device thinks the reply comes from the server it requested.

When header fields are modified by an intermediate equipment here the *OpenFlow* controller), it invalidates protocols' checksums. Typically, *IP*, *TCP* and *UDP* use checksums [17] to protect themselves from data corruption. Thus the controller has to be careful about recomputing each packet's checksum when one or more fields are modified within a packet. Moreover one must be extra-careful with *TCP* which includes part of the *IP* header in its checksum (including addresses). Hence in the present situation, both the *IP* and *TCP* checksums must be re-computed on every modified packets.

Now that the controller is able to intercept user traffic and redirect it to a chosen server, it becomes feasible to implement an *HTTP* redirection. Following section presents how the web server is configured in order to implement the *HTTP* layer.

3.5.2 Web server

Following the same guidelines about not re-implementing basic protocols seen in section 3.3, using an *HTTP* server to implement that layer seems obvious. They are highly configurable and efficient to reply to *HTTP* requests.

In the present situation, the web server is only intended to redirect every requests using a return code. A couple *HTTP* codes fulfill this goal, namely 301 and 302. The former tells the client that the document he asked for has moved permanently to a different location whereas the latter notifies that the document has moved temporarily. When a web browser receives one of these responses to a request, it will follow the *URL* present in the *Location HTTP* header field. If the redirection is permanent, later requests to the initial *URL* will result in an internal redirection. As an example if a browser receives a permanent redirection when it asks for `www.google.com`, it will not be possible for the user to access this website anymore. That is why the preferred response code is 302 here.

Additionally because Operating Systems do not provide standard API to access low level network information of a peer such as it's MAC address, the Apache web server is unable to populate the URL with the correct GET parameters. Moreover, it has little information about the network topology making it a weak point to decide the zone in which the user is connected. That zone allows to redirect the user to the correct web portal with the correct visual. For these reasons, we propose to delegate these tasks to the OpenFlow controller. Indeed it has all the information in hands to take care of this job.

In this proposal, the web server is only in charge of setting up and maintaining *TCP* states as well as crafting *HTTP* responses. Traffic emitted from user devices is intercepted and injected onto a controlled web server. It replies to any *HTTP* requests with a redirection.

Next section details how the *OpenFlow* controller modifies part of the data flow in order to insert the user device network information inside the redirection URL.

3.5.3 OpenFlow controller

When the web server replies to a request, the OpenFlow controller modifies part of the response. It is important to remember that it's the controller

who forwards every packets from OpenFlow switches to the web server. In order to modify the response, the controller first needs to identify it. The implementation searches at a specific offset of the TCP payload for the "Location:" string. To speed up the lookup, only packets with a non-zero payload and the PUSH flag set are taken into account. The offset remains fixed for a specific web server, indeed it replies with the same response all the time. Hence it is easy to calibrate the controller during its startup sequence in order to find the correct location's offset.

Once the response is identified, the controller chooses a captive portal to redirect the user to. The configuration details are out of the scope of this paper but as an example users connected to the `backery` SSID might be redirected to the `/zone/backery` *URI* whereas others to `/zone/welcome`. Parameters about the user device and any others are then appended to the *URI*. A sample *URL* might look like this:

```
http://portal.com/z/b/?mac=00:43:21:f3:32:43&ip=10.10.1.1
```

The crafted *URL* is then inserted in place of the "Location:" field's value replacing the dummy URL. The modified packet is then sent to the user device. Because the size of the original packet is modified, *TCP* sequence and acknowledgment numbers are corrupted. Indeed TCP uses the size of transmitted packets to increase sequence numbers and acknowledge data segments. Here a *man-in-the-middle*, the controller, has modified the data being sent by the server. Hence the client received something different from what the server sent.

Next section details how the controller deals with these numbers in order to keep both sides synchronized.

3.5.4 Dealing with TCP

The *URL* modification introduced a size difference between the original packet sent by the server, with the sequence number Seq_i and the size len_i, and the one received by the client. This difference is noted Δ_s.

When the client acknowledges the packet, it uses the equation (3.2) to generate the following acknowledgment number:

$$Ack'_i = Seq_i + len_i + \Delta_s + 1 \tag{3.3}$$

The problem lays in the fact that the server expects the data to be acknowledged until:

$$Ack_i = Seq_i + len_i + 1 \tag{3.4}$$

RFC 793 which defines the *TCP* protocol states that a peer should reset the connection if it receives data out its receiving window that is between the last acknowledged segment and the last packet's sequence number plus its size:

$$Ack_{last} < Ack_i < Seq_n + len_n \tag{3.5}$$

As a result, the acknowledgment sent by the client must be modified in order to be part of the server's receiving window. Formally, the acknowledgment number has to be decreased by Δ_s:

$$\begin{aligned} Ack_i'' &= Ack_i' - \Delta_s && (3.6)\\ &= Seq_i + len_i + 1 + \Delta_s - \Delta_s && (3.7)\\ &= Seq_i + len_i + 1 && (3.8)\\ &= Ack_i && (3.9) \end{aligned}$$

When the server receives the acknowledgment, it sees the correct number Ack_i.

On the other hand, the sequence numbers are also biased by the packet's modification. Indeed the next packet sent by the server will have a sequence number equal to:

$$Seq_{i+1} = Seq_i + len_i \tag{3.10}$$

whereas the client expects:

$$Seq_{i+1}' = Seq_i + len_i + \Delta_s \tag{3.11}$$

Reusing the operation done on acknowledgment numbers, the controller modifies the sequence numbers of packets emitted by the server in the following manner:

$$Seq''_{i+1} = Seq_{i+1} + \Delta_s \quad (3.12)$$
$$= Seq_i + len_i + \Delta_s \quad (3.13)$$
$$= Seq'_{i+1} \quad (3.14)$$

These two simple operations synchronize the sequence and acknowledgment numbers between the two TCP peers. This allows to modify the TCP payload in order to instrumentalize applicative protocols.

Corner cases exist when the redirection packet is not big enough to add all the data required. The packet must then be split into multiple ones and the controller has to deal accordingly with the acknowledgments (an algorithm is presented in appendix)

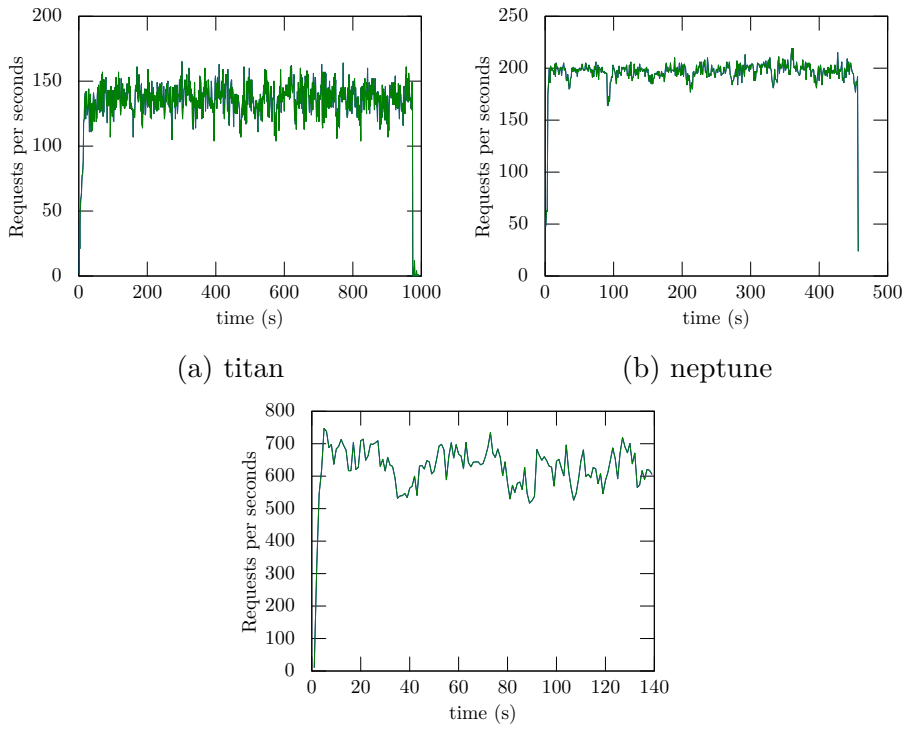
Next section presents the performance analysis of the portal redirection implementation.

3.5.5 Performance

To measure how well the implementation performs, the first thing to look at is the maximum rate at which *HTTP* requests are redirected. The redirection rate is later noted ρ. Similarly to the bandwidth experiment presented in section 3.4.3, the same set of 10 machines concurrently run an *HTTP* bencher called *ab* [1]. The web server is configured using the *RedirectMatch* directive [2] to create redirection responses.

The first three figures 3.8 show ρ over time for the three least powerful hardware independently. Valuable information lays in these plots as they show stable rate over time. They also demonstrate a high correlation between ρ and the *CPU* grade. Indeed a factor 3 exists between the venus machine (figure 3.8c) and the other two (figures 3.8a 3.8b). Even for lightweight hardware, the implementation is able to redirect up to 150 requests per seconds. This is largely enough to handle thousands of concurrent users as shown in figure 3.9. The maximum redirection rate is below 70 requests per seconds.

Additionally, a measurement of the requests' latency was made during the same test. The idea is to ensure that the overhead introduced by the controller is not too big for end-users. Figure 3.10 presents box plots of the request latency for each hardware. The titan is highly impacted compared to the others because of its poor hardware capacity (the benchmark uses



(a) titan

(b) neptune

(c) venus

Figure 3.8 – Number of HTTP requests redirected per seconds for different hardware

to much resources). The other hardware demonstrate that there is little to no overhead when the controller is not at its limit.

To reach the controller's ρ limit, the other machines were added to the experiment. Results are plotted in figure 3.11. The upper line represents the global redirection rate whereas each machine rate is represented by a lower line. This plot clearly highlights the maximum ρ achievable by the controller with around 1200 requests per seconds. On the other hand, all the switches are below 200 req/s which is lower than the venus's maximum for example.

Being able to redirect around 1200 HTTP requests per seconds is way higher than expected. Indeed because the solution scales horizontally by multiplying the number of controllers, it was planed to use a number of controllers to reach few thousands of users. Here the rate is theoretically enough to handle tens of thousands of concurrent users. Of course the experiment does not reproduce real user behavior as each HTTP bencher make as much requests as possible: when they receive a response, they send another request. In real life, users make few requests before authenticating.

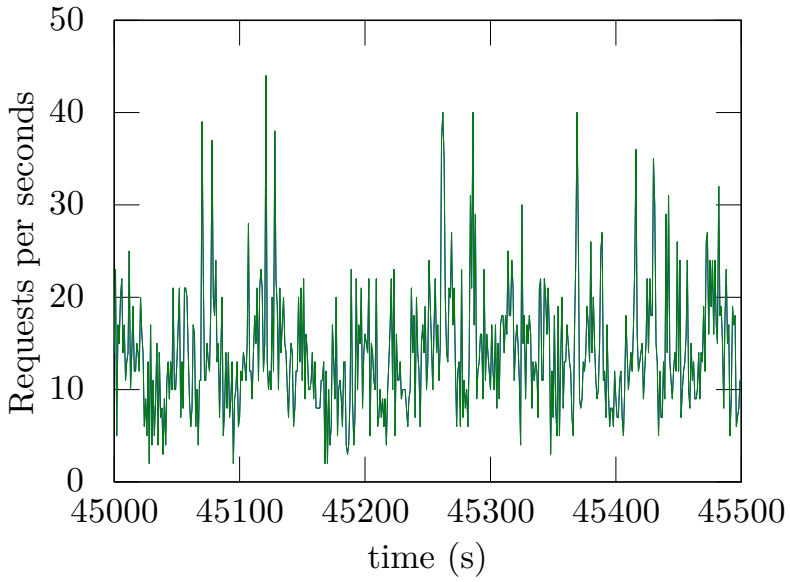


Figure 3.9 – Redirection rate of unauthenticated users on real hardware (3000 connected users)

Looking at the request rate alone is not enough to tell if the current implementation delivers the proper quality of service when pushed at its limit. When reaching the controller's limit, the latency should not go over the top making the whole system unusable. Figure 3.12 shows a box plot of the latency for each machine during the previous benchmark. It demonstrates that the median latency is below 25ms which is acceptable. Few requests are being delayed up to hundreds of milliseconds which is still insignificant for end-users. Compared to the first box plots presented in figure 3.10, latency has been multiplied by 4 but is still kept within an acceptable range.

Overall, results are higher than expected in the first place with a very high potential. The scalability factor is great because controllers can be cloned in order to scale horizontally. Furthermore, this leverages the flexibility provided by the data center infrastructure allowing to provision controllers on-demand.

3.5.6 Summary

The process presented here is to the best of our knowledge the first attempt to use OpenFlow switches to instrumentalize application protocols. The implementation proves to behave decently in regard with several metrics: throughput, latency and request rate. The proposal uses OpenFlow

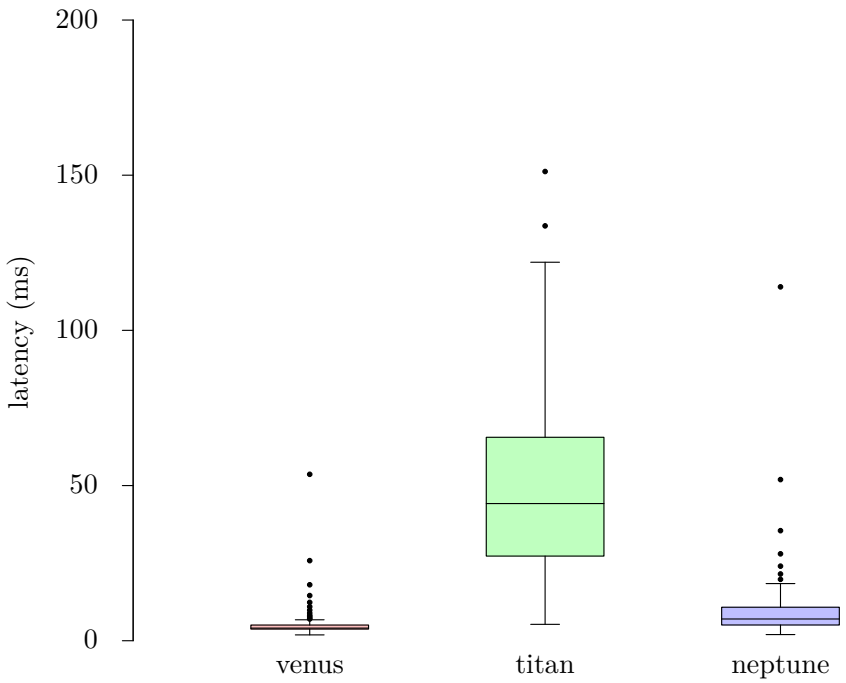


Figure 3.10 – Box plots of request latencies for the three different hardware

equipments to intercept and send raw packets emitted by user devices to an OpenFlow controller. In order to exempt a complete network stack implementation within the controller, the patented solution demonstrates the feasibility of having another network stack to take care of the user traffic.

The implementation permits to redirect user traffic to an external captive web portal. The key factor here is that the redirection response is modified by the controller to add the user device network information. It is an example of cross-layering via OpenFlow. These information are crucial for the remote captive portal to differentiate devices within a private network and notify the controller about newly authorized devices. The solution meets the requirements of being transparent for end-users and web browser independent. Moreover new features can be implemented within the controller: for instance, the redirection URL can be signed to prevent modification from end-users. This is a clear improvement over current implementations. These new features are implemented inside the controller only. Traditionally, such mechanism is absent from network equipments and would require an upgrade of the embedded software to include this feature. In the present situation, one can imagine common APIs between the OpenFlow controller and the remote captive portal to exchange keying materials to sign information passing by the user browser.

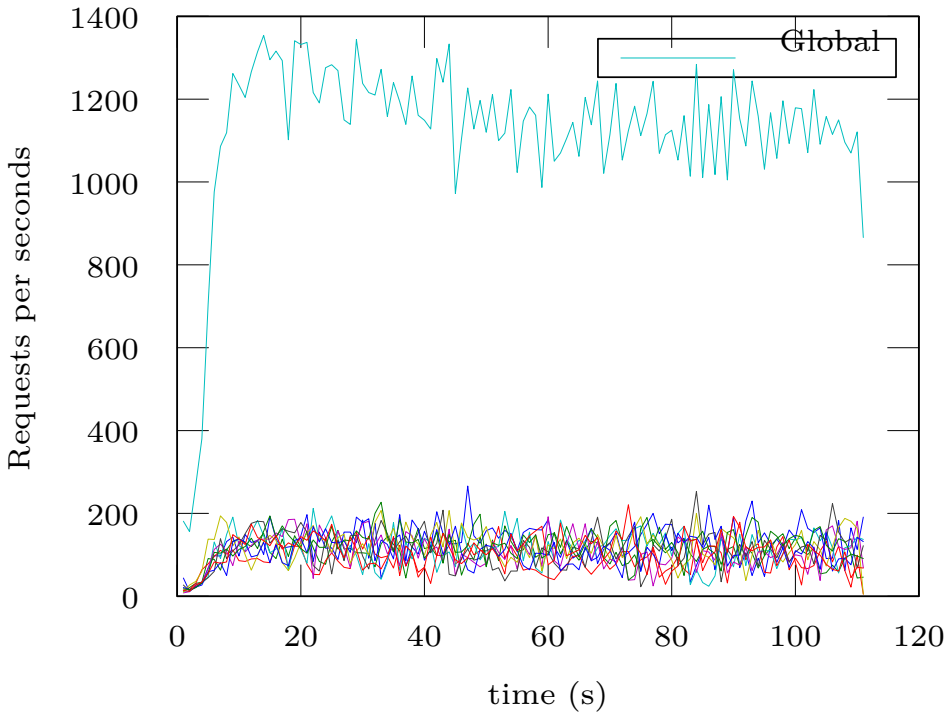


Figure 3.11 – Number of HTTP requests with ten concurrent machines during a 2 minutes benchmark

The results of this chapter have been submitted to an International conference [13] and are pending for approval. Moreover, a patent [15] has been filed in the European Patent Office and is being treated since the begin of this year.

Finally, the proposed solution modifies applicative protocols on-the-fly. The technique is known as *man-in-the-middle* in which an entity in the data path actively modifies payloads. Although in the present context, the modification introduced by the controller are harmless, one could modify any kind of traffic to implement any kind of "features". It outlines the new threat of having network equipments controlled by external entities and the need of using secure protocols when exchanging sensitive data.

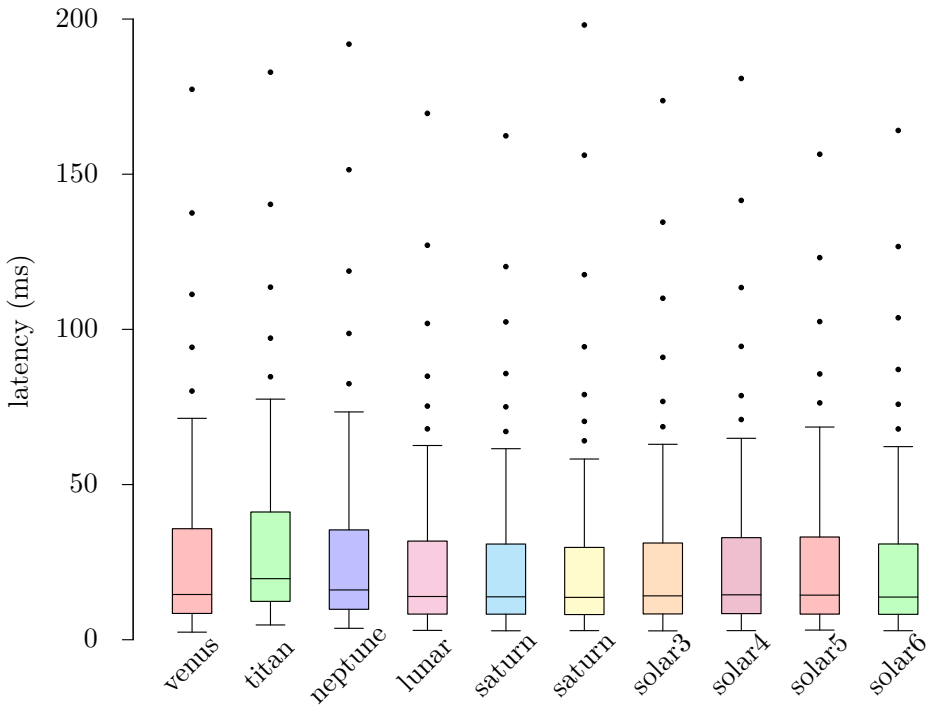


Figure 3.12 – Box plots of requests latency during a 2 minutes benchmark

Conclusion and Perspectives

This manuscript has been a great opportunity to present the need of accessing cross-layer information for network applications. It demonstrated, through a concrete example, that these pieces of information are key when implementing custom network behavior. Additionally, most remote applications can not directly access such cross-layer information. The presentation focused on a specific network application: controlling user access in private networks. Chapter 1 presented the current state of the art regarding user authentication and network access control. It gave a solid background to fully understand the ins and outs of controlling user access: who accesses what ? User authentication responds to the former question whereas cross-layer information permit to build advanced firewalling rules. The keystone which tight them together is the ability for the solution to bind the user identity to its device. A number of authentication methods were presented in this chapter giving different kinds of trust about the user recognition with a trade off between security and user-friendliness. Additionally, multiple network protocols to transport user authentication were presented as well as techniques to filter network traffic based on cross-layer information.

Then a novel architecture was presented in chapter 2. It permits to mutualize a network controller by hosting it in a public Cloud. It leverages the usage of lightweight Wi-Fi access-points on site to perform the physical network filtering of users as well as the captive portal enforcement. In order for the captive portal to differentiate devices within the same Local Area Network, the on site equipments add network information inside an HTTP redirection: when an unauthorized device tries to perform an HTTP request outside the network, the equipment redirects it to the captive portal. The target URL is populated with additional parameters to send to the captive portal. This is a practical example of sharing cross-layer information.

To authenticate users, the session border controllers perform a RADIUS

request when users post their credentials on their interface. It is the role of the captive portal to build that request from the user web browser. This can be achieved through a regular HTML form or by using more complicated scripting. Because each vendor implements its own interface, the captive portal must recognize the type of access-points which redirected a user and accordingly forge the correct request. A model was presented in section 2.3.1 to describe each vendor: how to recognize them (signature), what method to use, what parameters on which host ? This architecture was deployed in various key projects for Ucopia since 2014 and participated to the effort of enabling cloud-based network access solutions.

Finally the last chapter of this thesis presented a novel cross-layer framework which enables a new way of managing users in a private network. It benefits from the OpenFlow protocol to remotely control border equipments in order to instrumentalize user traffic. This innovative approach solves a specific cross-layer problem but can be extended to a wider set of problems. A successful implementation of the framework permits to redirect unauthenticated users to a web captive portal with cross-layer information held in the redirection URL. This allows the captive portal to correctly identify devices belonging to the same private network and to notify the OpenFlow controller about newly authenticated devices. The implementation is platform independent and provides high performance with an average of 1200 HTTP redirections per seconds. Additionally, the implementation scales horizontally by adding more OpenFlow controllers as their tasks are independent from each others.

While OpenFlow is originally intended to instrumentalize network protocols, up to the transport layer, the contribution presented in the last chapter overcomes this limitation by providing a way of intercepting, injecting and modifying user flows. The implementation makes it possible to transmit cross-layer information about user devices to a central web portal.

Despite the lack of OpenFlow capable equipments in real networks today, the keen interest of Wi-Fi vendors to implement it in their access-points offers a number of opportunities. Indeed no other equipments on-site is required. Plus setting up this solution is easier compared to traditional access control appliances: one only needs to let their equipments get controlled by our remote controller and configure the captive portal for all their sites in a unique place. Our solution can bring network access as a service and may open individual networks to welcome guests.

In parallel, lots of effort have been made within the Ucopia's R&D team to improve the Ucopia solution's performance. Indeed, it is a key factor in this architecture as it provides the web portal, the user database and the authentication server. Ucopia solution is now able to handle more than 20000 concurrent users by itself and aims at reaching 100000 next year.

This thesis' outcomes have brought great benefit to the company both immediate and in the long term. The architecture described in chapter 2 has already been deployed in various projects and the market's demand is increasing. Regarding the OpenFlow story, the company now has a first foot inside the SDN world with a very promising patent.

Still both architectures lack features in order to be fully compliant with customer requests. The main problem is that the user logs are no longer recorded: indeed with no controller on-site, it's hard to store the user's activity. One proposal is to use the information sent by the access-points via the *syslog* protocol in order to retrieve visited URLs or even packets logs. An implementation of this is being tested but still has poor performances. Moreover, the *syslog* messages are sent in plain text over the Internet possibly exposing sensitive user data.

On the other hand, the OpenFlow architecture implementation is only partially complete. Though the main technical lock has been resolved, an other challenge remains: building up a set of firewalling rules within a constraint environment. Indeed among the OpenFlow equipment diversity, small hardware have limited memory. In such cases, the flow table size might be tight to hold a large number of rules. Future work aims at studying that problem and finding ways to decrease the number of rules to control users. One proposition is to aggregate rules used by different profiles.

This thesis has open lots of perspectives both on the industrial and scientific sides. First of all the implementation of a complete prototype for network access control with OpenFlow equipments would highly benefits the Ucopia company by opening a new market full of opportunities. Second of all, Network Function Virtualization could bring even more flexibility to our proposal and might fill the gaps of the current implementation.

Mainly given the orchestration capabilities of SDN protocols over NFV, it becomes feasible to instantiate Network Functions on demand from an SDN controller. This could allow the implementation of lawful functions whenever needed in order to be compliant with law requirements. Moreover

network functions can implement capabilities absent from SDN equipments and extend easily a given setup.

We believe that NFV gives a promising perspective for network access control and that a thesis on that subject can make a lot of sense.

Appendix A

Dealing with over sized packets

In the last chapter of this thesis, a presentation of an OpenDaylight bundle was made. It is in charge of forwarding raw traffic coming from an OpenFlow equipment to a dedicated server and identifying HTTP redirections sent to the user. These packets are then modified to inject valuable data about the user device. This attributes list might grow the packet beyond the MTU. This would result in a packet drop at the switch.

To cope with this situation, the controller must detect and split such packets before sending them to the client. Following acknowledgments must be dropped by the controller until the last one is received. Indeed, the client will acknowledge multiple segments whereas the server sent only one. Formally, when the server modifies a packet, it computes the last expected acknowledgment number ACK_{last}. Then it splits the packet into chunks which fit the MTU and sends them in order to the client. For every following acknowledgments (sent by the client), the controller checks that they are lesser than ACK_{last} and drop them. Whenever the last acknowledgment is received, the controller forward it (minus Δ_s) to the server.

Algorithm 1 presents the function which handles all received packets. First the function gathers the recorded state of the TCP stream from packet's information (Ethernet and IP addresses, TCP source port number). This state holds valuable information about the client and the server in order to perform the NAT as well as ACK_{last} when a packet is modified inside the stream. Then the function branches depending on the side of the packet: when it comes from the server, it tests of it needs to modify the packet and if so modifies it and sends it in chunks (if needed). When the packet comes from a client, it verifies that it acknowledges up to ACK_{last} before forwarding it to the server. Of course the concrete implementation of

this function does more processing to detect new TCP connections, 4-way termination handshake or perform NAT correctly.

Algorithm 1 Over sized packets

```
function receivePacket(buffer packet)
    state ← getState(packet)                    ▷ Get recorded state from packet
    if isFromServer(packet) then
        if shouldModify(packet) then
            packet' ← modify(packet)
            Δ_s ← size(packet') − size(packet)
            state.ACK_last ← packet.SEQ + Δ_s + 1
            i ← 0
            while size(packet') > MTU do
                i ← i + send(packet'[i : i + MTU])
        else
            send(packet)
    else                                        ▷ Packet comes from a client
        if state.ACK_last > 0 then
            if packet.ACK < state.ACK_last then
                return PACKET_IGNORED
            else
                packet.ACK ← packet.ACK − Δ_s
        send(packet)
    return PACKET_CONSUMED
```

The algorithm heavily relays on the configured MTU between the client and the server but this parameter is never transmitted directly and does not take into account the OpenFlow tunnel. Thankfully, a TCP option exists to bound the maximum size of the payload. It is called the MSS (Maximum Segment Size). In general, the MSS reflects the MTU at the TCP layer: $MSS = MTU - size(IP) - size(TCP)$. In our situation, the controller is able to read the MSS during the 3-way handshake at the beginning of every connection. Additionally, it can modify this value if it is too high to fit inside the OpenFlow tunnel.

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Bibliography

[1] ab - Apache HTTP server benchmarking tool. Technical report, The Apache Software Foundation.

[2] Apache HTTP Server Documentation. Technical report, The Apache Software Foundation.

[3] Service Name and Transport Protocol Port Number Registry. Technical report, IANA.

[4] Squid web proxy project.

[5] The SquidGuard project.

[6] ISO/IEC 7498. Technical report, ISO, 1994.

[7] Subscriber Identity Module - Mobile Equipment Interface Specification. Technical report, European Telecommunications Standards Institute, 1994.

[8] White paper on "Network Functions Virtualisation". Technical report, SDN and OpenFlow World Congress, 2012.

[9] SDN for Wi-Fi OpenFlow-enabling the wireless LAN can bring new levels of agility. White paper, 2014.

[10] Hervé Aıache, Vania Conan, Jérémie Leguay, and Mikaël Levy. Xian: Cross-layer interface for wireless ad hoc networks. *MEDHOCNET 2006*, 2006.

[11] Jon Dugan Ajay Tirumala, Feng Qin. Iperf: The TCP/UDP bandwidth measurement tool. 2005.

[12] Nadarajah Asokan, Valtteri Niemi, and Kaisa Nyberg. Man-in-the-middle in tunnelled authentication protocols. In *Security Protocols*, pages 28–41. Springer, 2005.

[13] G. Pujolle B. Villain, J. Ridoux. SDN Based Network Access Controller: a First Milestone. *To be Published*, 2015.

[14] J. Rotrou B. Villain, J. Ridoux. Mutualized OpenFlow Architecture for Network Access Management. *Cloud'Net*, 2014.

[15] P. Borras B. Villain, J. Rotrou. Procédé de contrôle d'accès à un réseau privé. Technical report, Ucopia - UPMC, 2015.

[16] Justin Pettit Ben Pfaff, Keith Amidon. Extending Networking into the Virtualization Layer. *ACM Workshop in Hot Topics in Networks*, 2009.

[17] James G. Wendt Brian M. Dowling, Christian J. Warling. Hardware checksum assist for network protocol stacks. Technical report, Hewlett-Packard, 1997.

[18] Raffaele Bruno, Marco Conti, and Enrico Gregori. Mesh networks: commodity multihop ad hoc networks. *Communications Magazine, IEEE*, 43(3):123–131, 2005.

[19] A. Rubens and W. Simpson C. Rigney, S. Willens. Remote Authentication Dial In User Service (RADIUS). Technical report, IETF, 2000.

[20] T. Chiueh C. Venkatramani. Design, implementation, and evaluation of a software-based real-time Ethernet protocol. *SIGCOMM '95*, 1995.

[21] Marco Conti, Silvia Giordano, Gaia Maselli, and Giovanni Turi. Mobileman: Mobile metropolitan ad hoc networks. In *Personal Wireless Communications*, pages 169–174. Springer, 2003.

[22] Marco Conti, Gaia Maselli, Giovanni Turi, and Silvia Giordano. Cross-layering in mobile ad hoc network design. *Computer*, 37(2):48–51, 2004.

[23] S. Muir D. Culler, A. Bavier. Operating System Support for Planetary-Scale Network Services. *First USENIX Symposium on Networked Systems Design and Implementation*, 2004.

[24] D. Meyer D. Farinacci, V. Fuller. The Locator/ID Separation Protocol (LISP). Technical report, IETF, 2013.

[25] D. Rauschmayer. *ADSL/Vdsl Principles: A Practical and Precise Study of Asymmetric Digital Subscriber Lines and Very High Speed Digital Subscriber Lines*. 1998.

[26] J. Romkey and H. Salwen D.D. Clark, V. Jacobson. An analysis of TCP processing overhead. *IEEE Communications Magazine*, 1989.

[27] Defense Advanced Research Projects Agency. Internet Protocol. Technical report, University of Southern California, 1981.

[28] Defense Advanced Research Projects Agency. Transmission Control Protocol. Technical report, University of Southern California, 1981.

[29] Gianni A Di Caro, Silvia Giordano, Mirko Kulig, Davide Lenzarini, Alessandro Puiatti, and Francois Schwitter. A cross-layering and autonomic approach to optimized seamless handover. In *WONS 2006: Third Annual Conference on Wireless On-demand Network Systems and Services*, pages 104–113, 2006.

[30] Patrick Raad Dung Phun Chi, Stefano Secci. An Open Control-Plane Implementation for LISP Networks. *IC-NIDC*, 2012.

[31] Takashi Egawa, Shin ichiro Hayano, and Fabian Schneider. Standardizations of sdn and its practical implementation. Technical report, 2014.

[32] Eric Thompson. MD5 collisions and the impact on computer forensics. *Digital Investigation*, 2005.

[33] Eugene H. Spafford. OPUS: Preventing weak password choices. *Computers & Security*, 1992.

[34] Open Network Fundation. Software-defined networking: The new norm for networks. White paper, Open Network Fundation, 2012.

[35] Open Network Fundation. Openflow switch specification version 1.3.3. Technical report, 2013.

[36] Paul Funk and Simon Blake-Wilson. Eap tunneled tls authentication protocol (eap-ttls). *Work in Progress*, 2004.

[37] H. Kim and N. Feamster. Improving network management with software defined networking. *IEEE Communications Magazine*, 2013.

[38] H. Sinohara. Broadband access in Japan: rapidly growing FTTH market. *IEEE Communications Magazine*, 2005.

[39] Youn-Hee Han, Heejin Jang, JinHyeock Choi, Byungjoo Park, and Janise McNair. A cross-layering design for ipv6 fast handover support in an ieee 802.16 e wireless man. *Network, IEEE*, 21(6):54–62, 2007.

[40] Horst Feistel. *Cryptography and Computer Privacy.* Scientific American, 1973.

[41] J. Linn. The Kerberos Version 5 GSS-API Mechanism. Technical report, IETF, 1996.

[42] M. Ahmed and C. Raiciu J. Martins. ClickOSandtheArtofNetworkFunctionVirtualization. *11th USENIX Symposium on Networked Systems Design and Implementation*, 2014.

[43] J. Postel. The TCP Maximum Segment Size and Related Topics. Technical report, IETF, 1983.

[44] J. Sermersheim. Lightweight Directory Access Protocol (LDAP): The Protocol. Technical report, IETF, 2006.

[45] I. Al Ajarmeh J. Yu. An Empirical Study of the NETCONF Protocol. *Sixth International Conference on Networking and Services*, 2010.

[46] Paul Safono and Mark B. James E. Weber, Dennis Guster. Weak Password Security: An Empirical Study. *Information Security Journal*.

[47] Janey C. Hoe. Improving the start-up behavior of a congestion control scheme for TCP. *SIGCOMM Conference proceedings on Applications, technologies, architectures, and protocols for computer communications*, 1993.

[48] P. Francis K. Egevang. The IP Network Address Translator (NAT). Technical report, IETF, 1994.

[49] J. Evarts L. Mamakos, K. Lidl. A Method for Transmitting PPP Over Ethernet. Technical report, IETF, 1999.

[50] M. Carbone and G. Catalli L. Rizzo. Transparent acceleration of software packet forwarding using netmap. *IEEE INFOCOM*, 2012.

[51] Luigi Rizzo. Netmap: A Novel Framework for fast Packet I/O. *USENIX Annual Technical Conference*, 2012.

[52] M. R. Salvador M. R. Nascimento, C. E. Rothenberg. Virtual routers as a service: the routeflow approach leveraging software-defined networks. *6th International Conference on Future Internet Technologies*, 2011.

[53] Thierry Turletti Marc Mendonca, Katia Obraczka. The case for software-defined networking in heterogeneous networked environments. *ACM CoNEXT*, 2012.

[54] Nick McKeown, Tom Anderson, and Hari Balakrishnan. Openflow: enabling innovation in campus networks. *ACM SIGCOMM Computer Communication Review*, 38 Issue 2:69–74, 2008.

[55] D. Malladi and R. Gillmore N. Bhushan, Li Junyi. Network densification: the dominant theme for wireless evolution into 5G. *IEEE Communications Magazine*, 2014.

[56] G. Mazza and G. Morabito N.B. Melazzi, A. Detti. An OpenFlow-based testbed for information centric networking. *Future Network & Mobile Summit*, 2012.

[57] O. M. E. Committee. Software-defined networking: The new norm for networks. Technical report, Open Networking Foundation2, 2012.

[58] Kaveh Pahlavan. *Principles of wireless networks: A unified approach*. John Wiley & Sons, Inc., 2011.

[59] Philippe Oechslin. Making a Faster Cryptanalytic Time-Memory Trade-Off. *Advances in Cryptology*, 2003.

[60] J. Schoenwaelder and A. Bierman R. Enns, M. Bjorklund. Network Configuration Protocol (NETCONF). Technical report, IETF, 2011.

[61] Justin P Rohrer, Abdul Jabbar, Egemen K Cetinkaya, Erik Perrins, and James PG Sterbenz. Highly-dynamic cross-layered aeronautical network architecture. *Aerospace and Electronic Systems, IEEE Transactions on*, 47(4):2742–2765, 2011.

[62] Charalampos Rotsos, Nadi Sarrar, Steve Uhlig, Rob Sherwood, and Andrew W. Moore. Oflops: An open framework for openflow switch evaluation. *Passive and Active Measurement*, 7192, 2012.

[63] S. McCanne and V. Jacobson. The BSD packet filter: a new architecture for user-level packet capture. *USENIX Winter 1993 Conference*, 1993.

[64] K. Vijayakumar and S. Sodhi S. Narayan, P.R. Lutui. Performance analysis of networks with IPv4 and IPv6. *IEEE International Conference on Computational Intelligence and Computing Research*, 2010.

[65] John F Shoch. Packet fragmentation in inter-network protocols. *Computer Networks (1976)*, 3(1):3–8, 1979.

[66] Steve Lord. Trouble at the Telco: When GSM Goes Bad. *Network Security*, 2003.

[67] P Syverson. A taxonomy of replay attacks. *Computer Security Foundations Workshop*, pages 187 – 191, 1994.

[68] C. Allen T. Dierks. The TLS Protocol Version 1.0. Technical report, IETF, 1999.

[69] R. Smelyanskiy V. Antonenko. Global network modelling based on mininet approach. *Second ACM SIGCOMM workshop on Hot topics in software defined networking*, 2013.

[70] Craig Leres and McCanne Steven Van Jacobson. libpcap: Packet capture library.

[71] Vanishree Rao Vipul Goyal, Adam O'Neill. Correlated-Input Secure Hash Functions. *Theory of Cryptography*, 2011.

[72] Xiaoyun Wang and Hongbo Yu. How to Break MD5 and Other Hash Functions. *Advances in Cryptology*, 2005.

[73] Liao Kuo-Hong Yen Sung-Ming. Shared authentication token secure against replay and weak key attacks. *Information Processing Letters*, 1997.

[74] Qian Zhang and Ya-Qin Zhang. Cross-layer design for qos support in multihop wireless networks. *Proceedings of the IEEE*, 96(1):64–76, 2008.

[75] Philip Zimmermann. Why I Wrote PGP. Technical report, 1991.